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-Technical Report-

Evaluating the Effectiveness of Various Blast Loading Descriptors as Occupant Injury Predictors for Underbody Blast Events

Presented at the ARL Workshop on Numerical Analysis of Human and Surrogate Response to Accelerative Loading, Jan 09 2014

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14. ABSTRACT
It is of considerable interest to developers of military vehicles, in early phases of the concept design process as well as in Analysis of Alternatives (AoA), to quickly predict occupant injury risk due to under body blast loading. The most common occupant injuries in these extremely short duration events arise out of the very high vertical acceleration of vehicle due to its close proximity to hot high pressure gases from the blast. The primary objectives of this paper are to conduct an extensive parametric study in a systematic manner so as (1) to determine if a single blast loading parameter is sufficient to adequately characterize the occupant injury, at least for the duration of typical blast events (0-20ms) and (2) to create look-up tables and/or an automated software tool that decision-makers can use to quickly estimate the different injury responses for both stroking and non-stroking seat systems in terms of such a parameter.

15. SUBJECT TERMS
DeltaV, EffectiveG,Specific Power, Blast, ROM, reduced order models, MADYMO, occupant, injury, pulse, loading, descriptor, calculator

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Evaluating the effectiveness of various blast load descriptors as occupant injury predictors for underbody blast events

Workshop on Numerical Analysis of Human and Surrogate Response to Accelerative Loading
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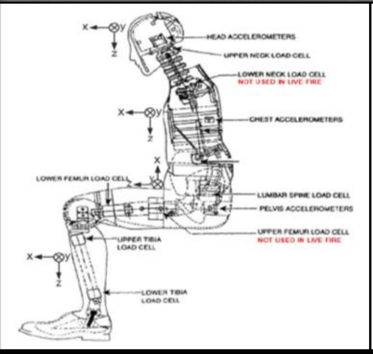
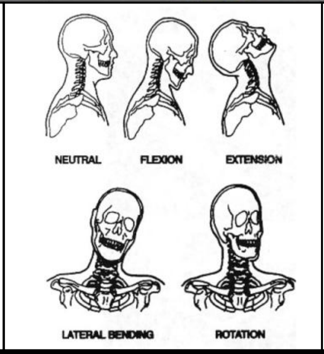
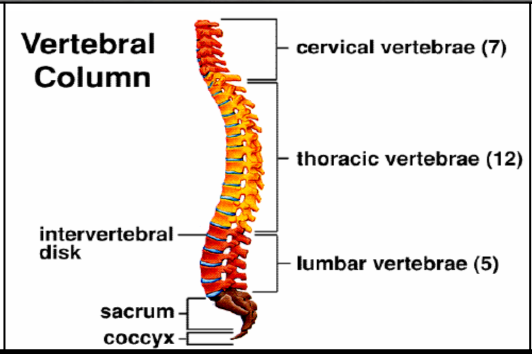
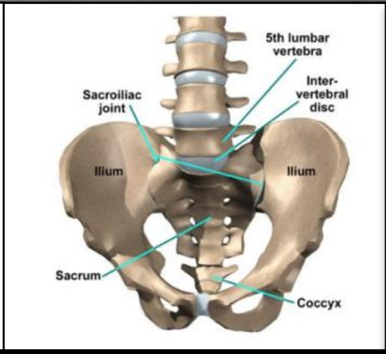
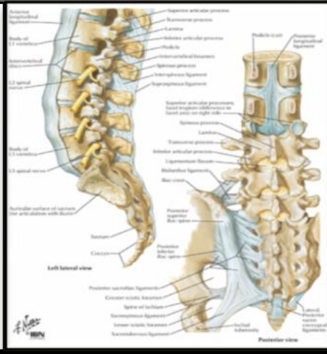






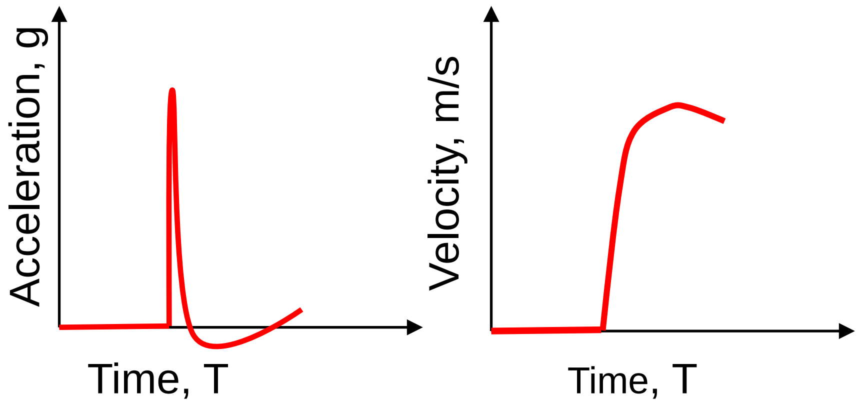




- It is a well known fact that underbody blasts have become one of the most widespread reasons for warfighter casualties in recent wars.
- Spinal injuries to occupants have particularly increased in theater from these roadside blast incidents, followed by tibia and lower leg injuries.
- The most common occupant injuries in these extremely short duration events arise out of the very high vertical acceleration of vehicle due to its close proximity to hot high pressure gases from the blast.
- It is of considerable interest to developers of military vehicles to assess occupant injury risk due to blast loading in the early phase of the design process.

Blast pulse and occupant injury

A typical blast loading pulse is triangular in shape and can be characterized by its peak acceleration (G_{peak}) or change in velocity (Δv) with or without considering the duration of the pulse (T).



Occupant injury risk is proportional to;

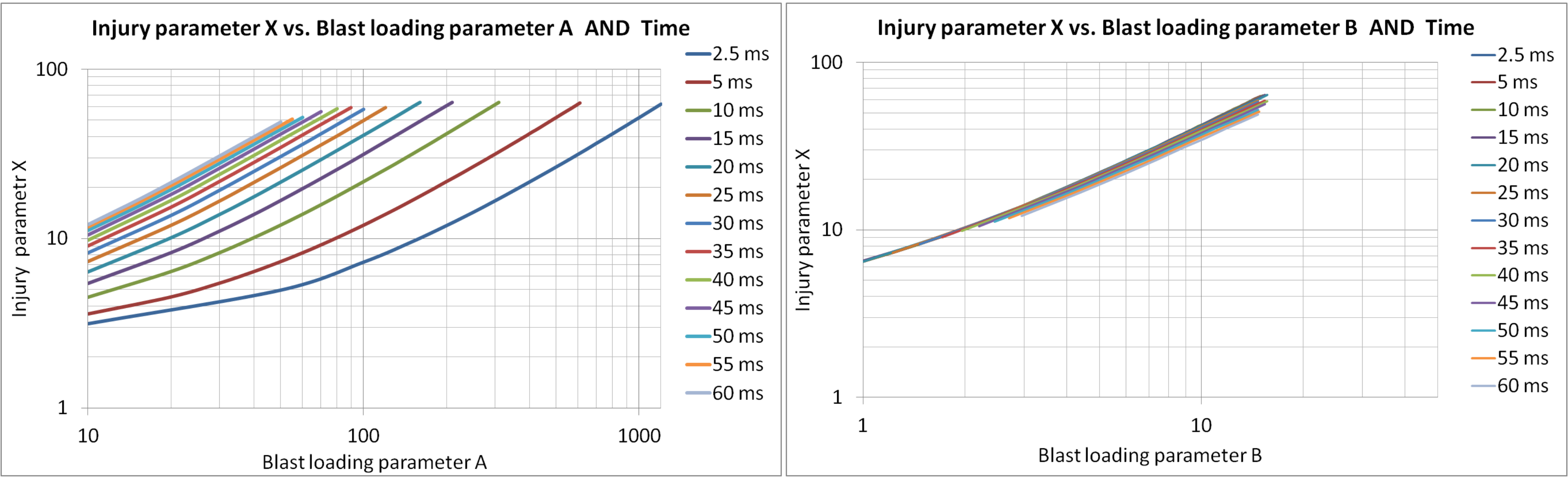
1. Peak acceleration, G_{peak} in g's
2. Time duration of the pulse, T in ms
3. Rate of onset of acceleration, $\dot{G}$ in g/ms
4. Change in velocity, Δv, in m/s
5. Direction of loading
6. etc.

It has been shown before that there is no single input parameter which can be used to effectively assess occupant injury. However, the design community often use peak acceleration, G_{peak} or Δv to determine the severity of any given pulse.

Earlier efforts to more adequately characterize the blast loading pulses include defining dependent variables such as Effective-g (slope of the velocity profile), and Specific Power (G_{peak} x Δv) with some success when compared against a few of the injury criteria.

Objectives

1. To determine If a single blast loading parameter is sufficient to adequately identify the occupant injury for the *duration of typical blast events (0-20ms).*
2. Effect of pulse “shape” on the occupant injuries
3. To create look-up tables/response surfaces for the different injury responses
   - for both stroking and non-stroking seat systems.

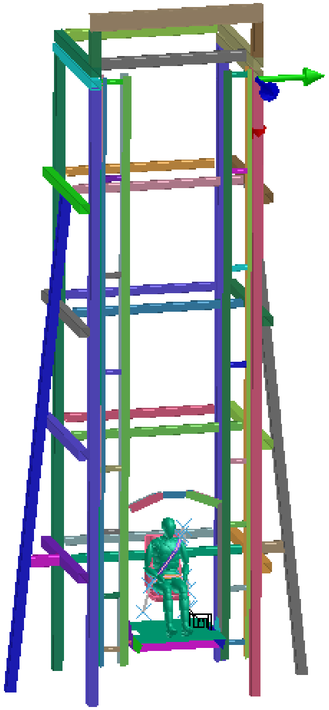


For the two notional plots above showing the same injury response shown against two different blast loading parameters (A and B including duration of the pulse T), the plot on the right (and hence that blast loading parameter) is preferred for the following reasons;

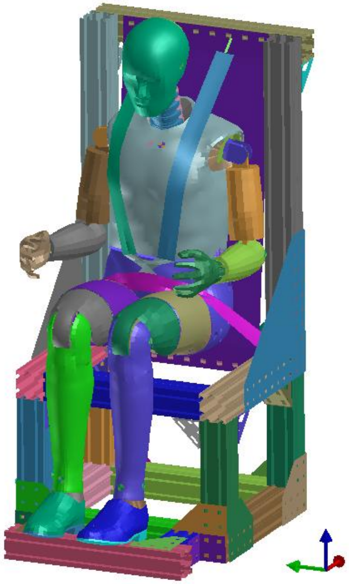
1. Less sensitive to change in pulse duration
2. Easier to establish a simple 2d relationship

Vertical drop tower test and simulation

Vertical drop tower test fixture



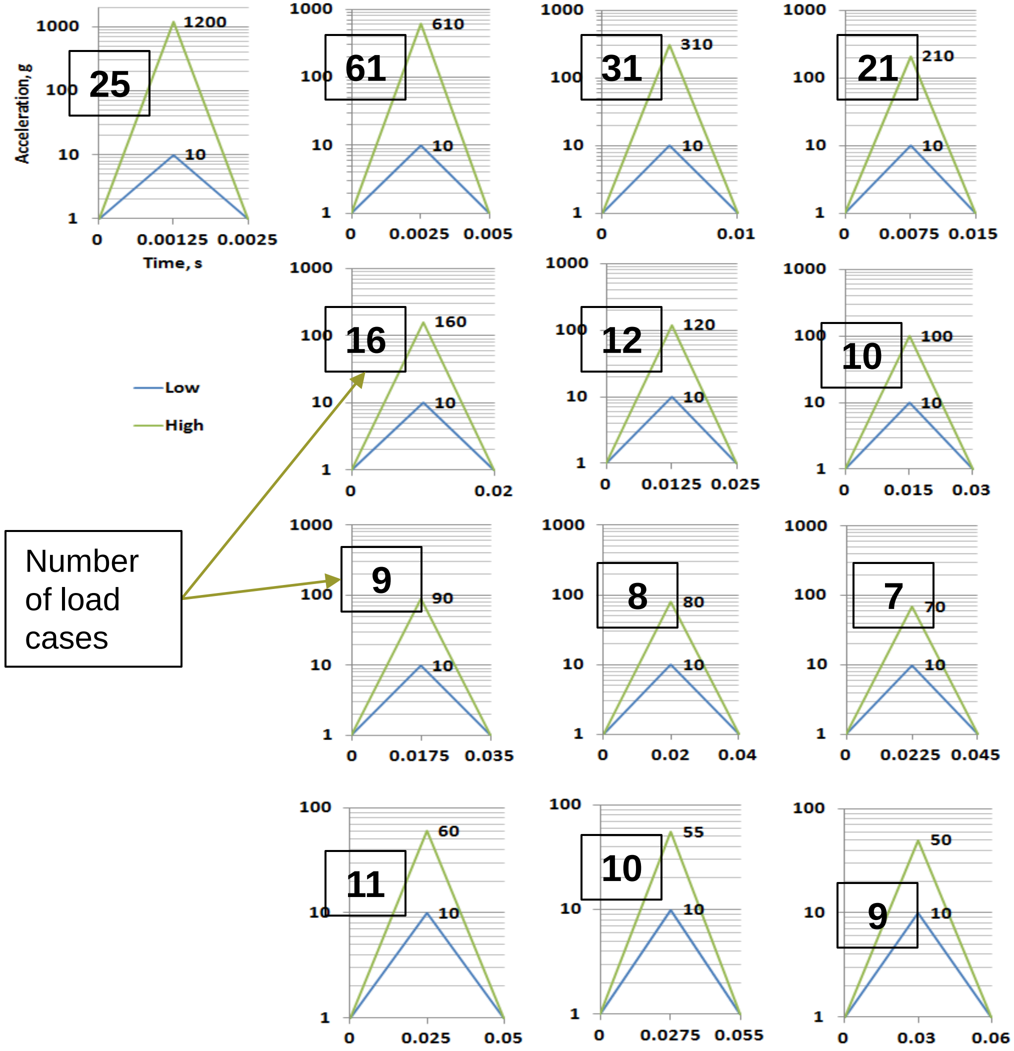
MADYMO Dynamic simulation model including Q-version of Hybrid III ATD



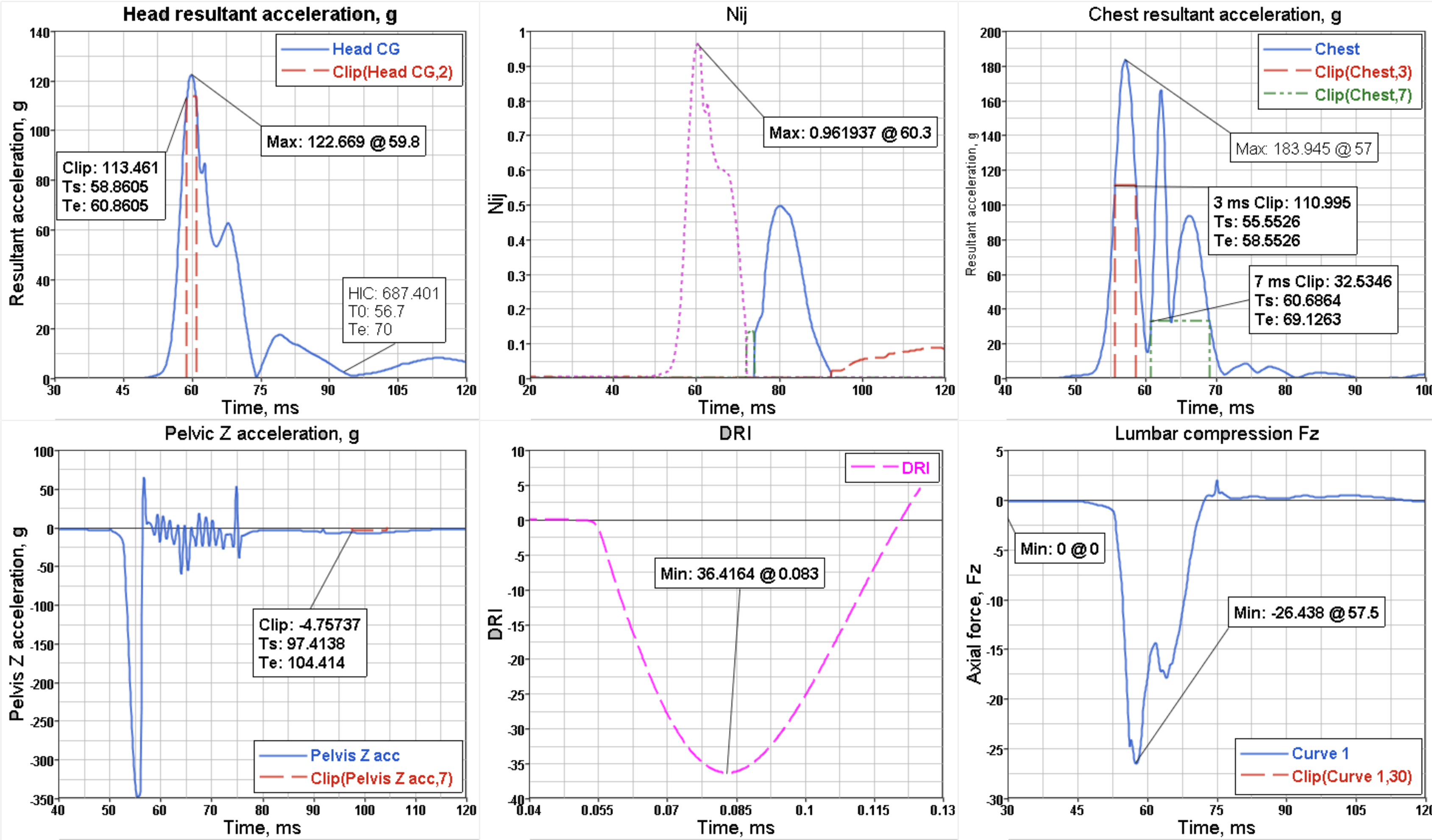
LSDYNA model with FTSS v7.1.6 finite element dummy

Parametric study

1. A triangular blast wave pulse was applied to the vertical drop tower sled.
2. A total of thirteen duration levels are studied; from 2.5 ms to 60 ms.
3. At each of these duration levels, peak deceleration was varied from 10g with 10g increments up to the point when Δv reached ~15m/s
4. A total of 230 runs were made each type of seat characteristic studied.
5. Three types of seat systems are; (i) Rigid (ii) Seat with a baseline EA (8kN) and (iii) A seat with softer EA (4kN)



Recording injury metrics



Response from the dummy especially pelvic acceleration and spine compression was quite noisy and did not sustain continuously long enough for those input pulses with higher onset rates.

- For each injury criterion the data is plotted against derived input quantities, viz.,

1. effective-g[1,3], defined as the slope of the integral of the velocity trace;

$$G_{eff} = \frac{1}{T}\int_0^T adt = \frac{V_f - V_o}{T}$$

2. Specific power[2], defined as;

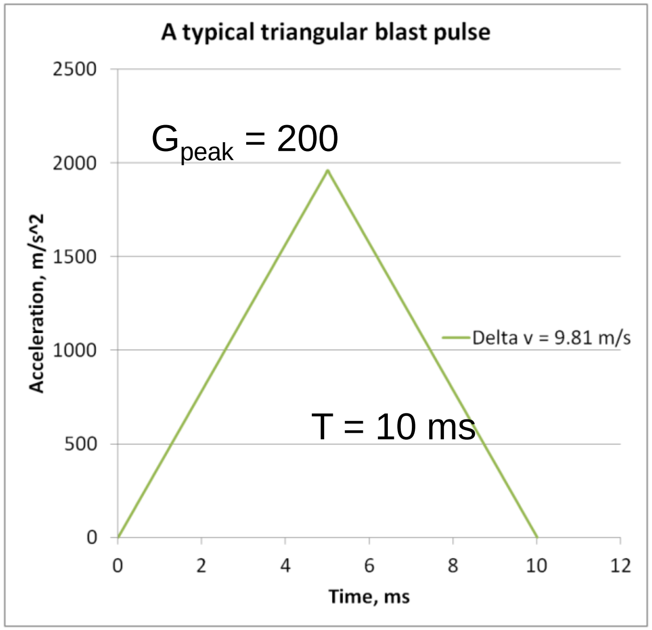
$$S = G_{peak} \times \Delta V$$

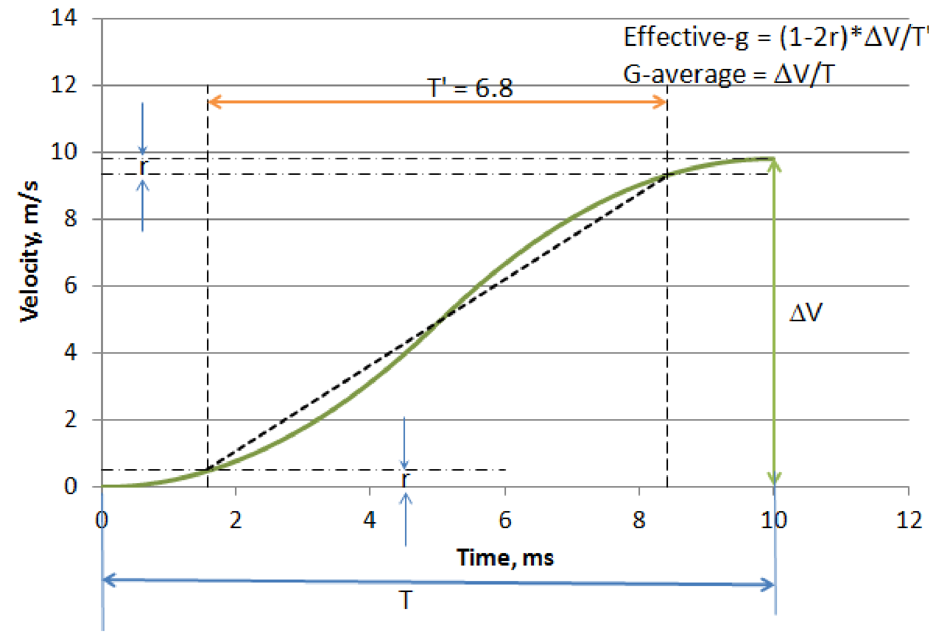
3. **ΔV, defined as;**

$$\Delta V = \int_0^T adt = V_f - V_o$$

Definition of Effective-g[1,3]

ΔV = 9.81 m/s





When, r = 5%;

Effective-g = 0.9* ΔV/T' = 132
G-average = ΔV/T = 100

$$G_{\mathrm{eff}} = G_{\mathrm{Peak}}\left(\frac{1+\sqrt{2r}}{2}\right) \qquad (0 \le r \le 0.5)$$

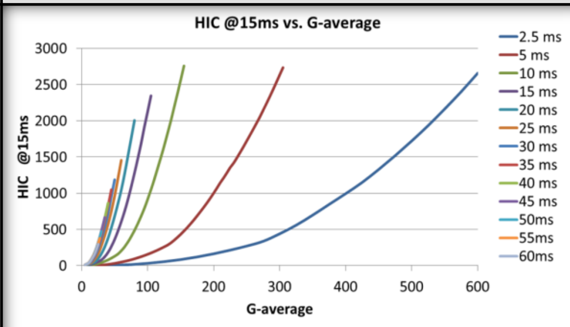
For triangular pulses used in this parametric study, the ratio of G_{eff} to G_{peak} is 0.6581 when r=0.05

Head Injury Criteria (HIC_{15})

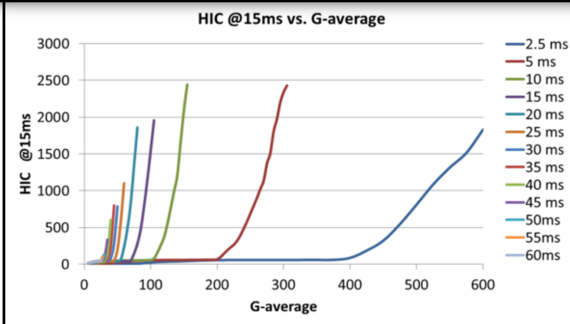
	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA
Effective-α	(chart 1)	(chart 2)	(chart 3)
Specific power	(chart 4)	(chart 5)	(chart 6)
ΔV	(chart 7)	(chart 8)	(chart 9)

Effective-α

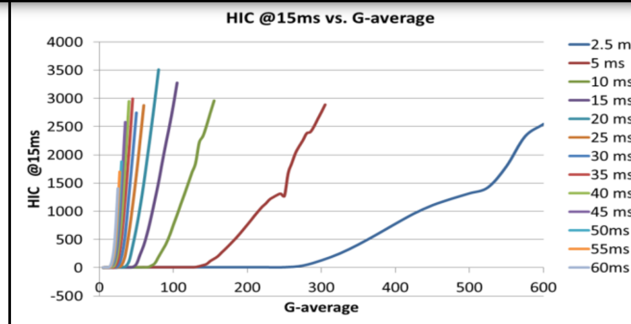
Rigid Seat



Seat w/ baseline EA

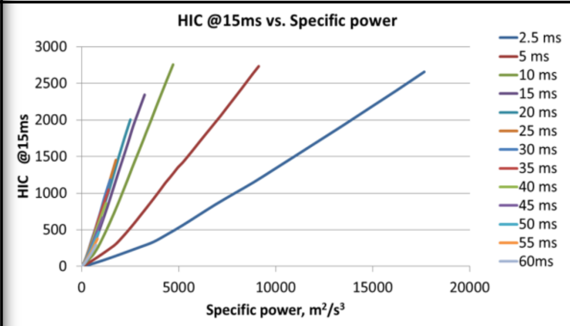


Seat w/ softer EA

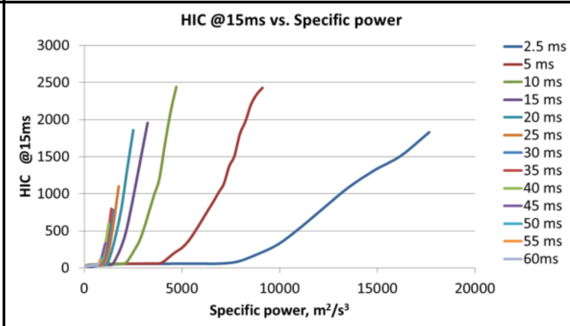


Specific power

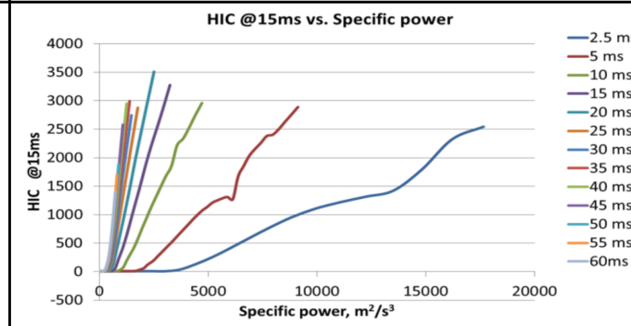
Rigid Seat



Seat w/ baseline EA

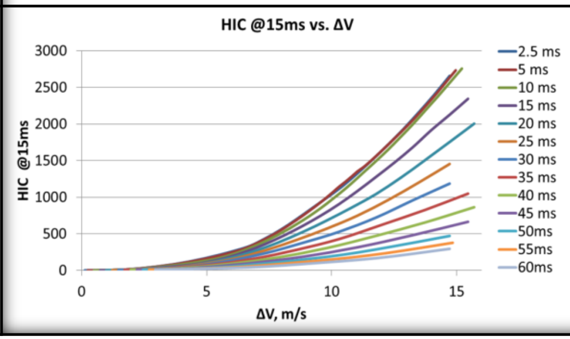


Seat w/ softer EA

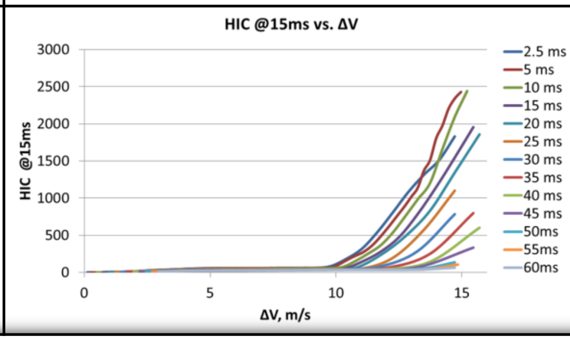


ΔV

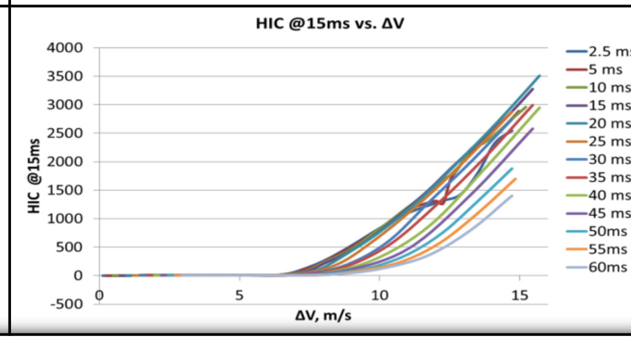
Rigid Seat



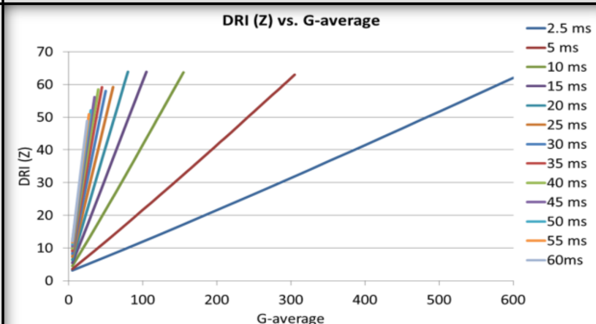
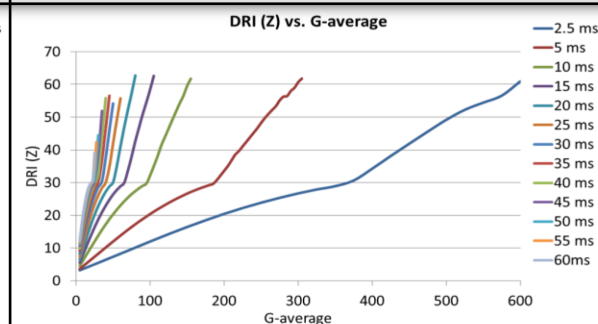
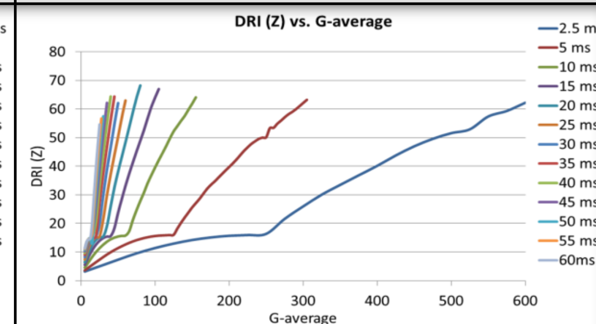
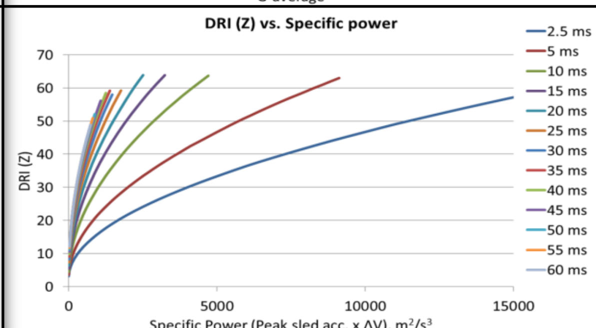
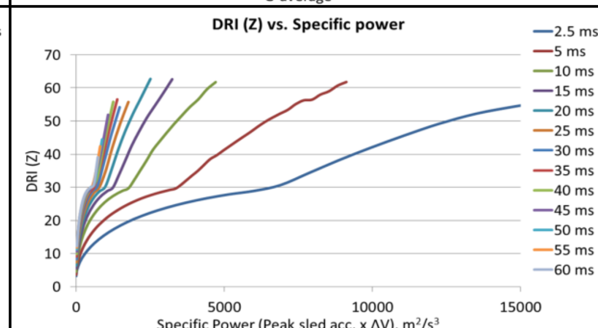
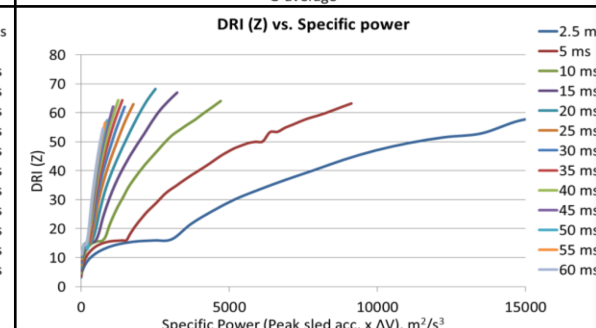
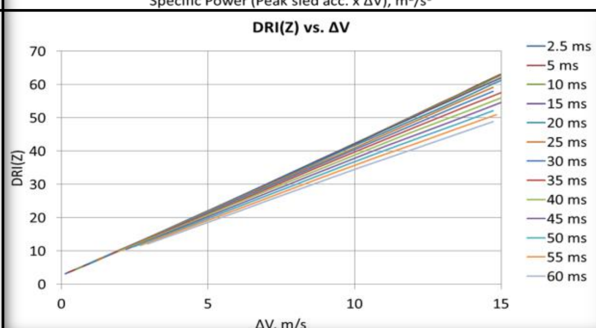
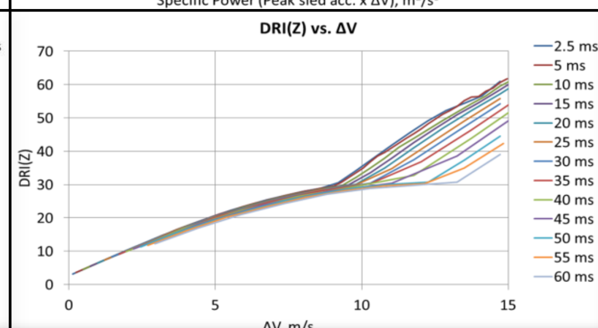
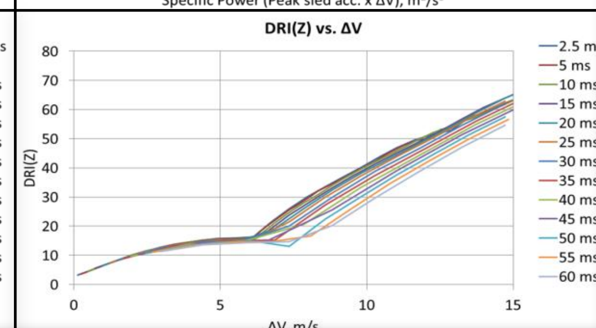
Seat w/ baseline EA



Seat w/ softer EA



DRI

	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA
Effective-g			
Specific power			
ΔV			

Observations and analysis

- None of the primary input pulse parameters considered in this study, by itself, is an indicator of occupant injury.
- One reason could be that our range of time duration of input pulses which ranged from 2.5 ms to 60 ms is too broad.
- Among the three loading parameters under consideration, Δv by itself, has the potential to be a single good indicator in the typical blast loading range of 0-20ms.
- For a wider range of T, any of these primary parameters in combination with the pulse duration can be used to estimate occupant injury.

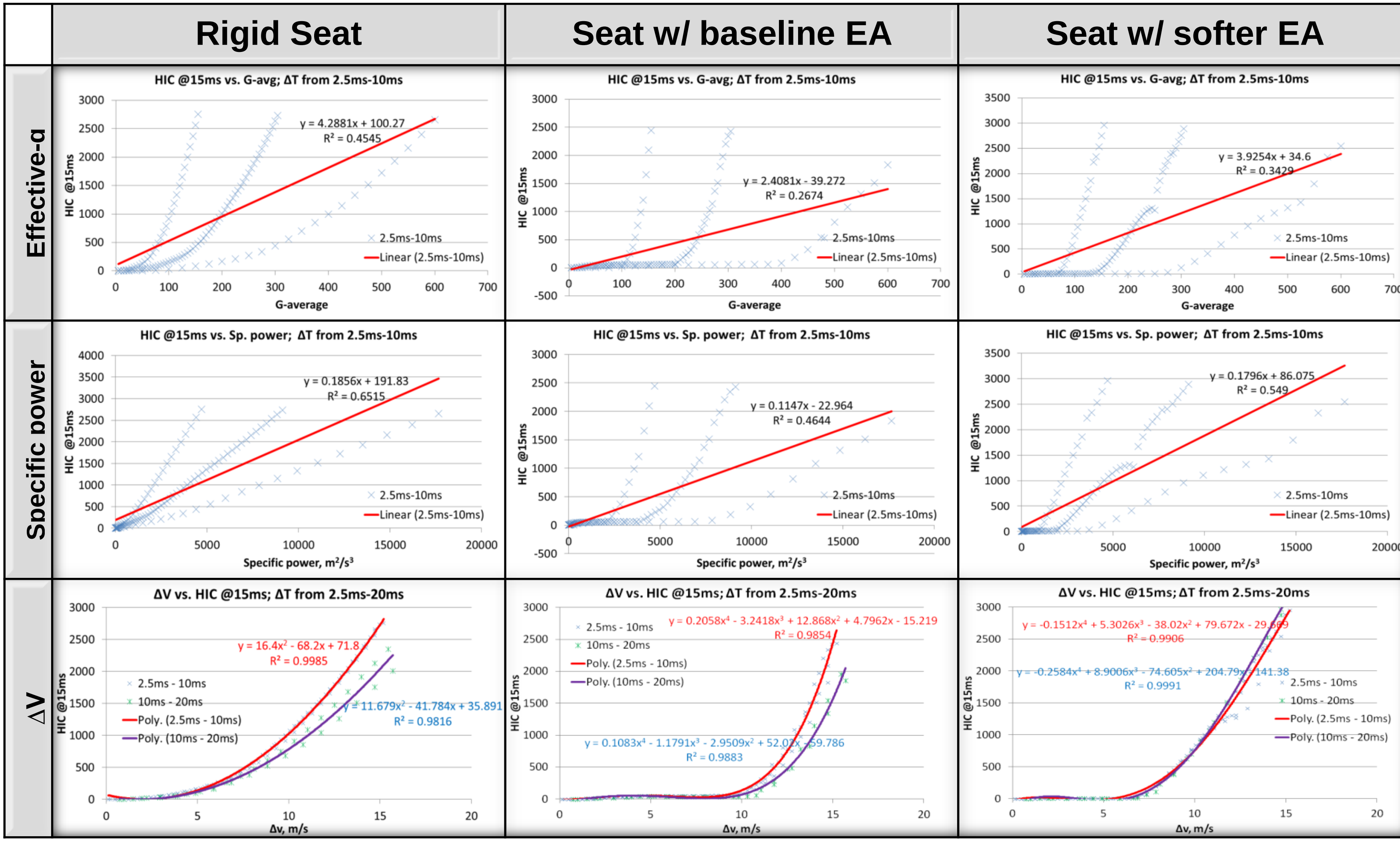
Analysis of pulse duration < 20ms

- Trend lines were drawn by grouping data points based on time duration of pulses, e.g., 0-10ms, 11-20ms and 21-60ms
- Correlation coefficients (r_c) are computed and tabulated for every injury criterion against the three variables (G-average, Sp. Power and ΔV)

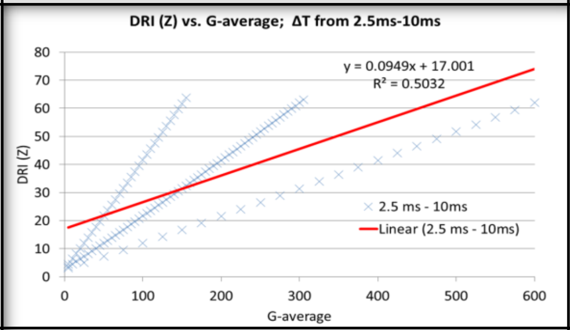
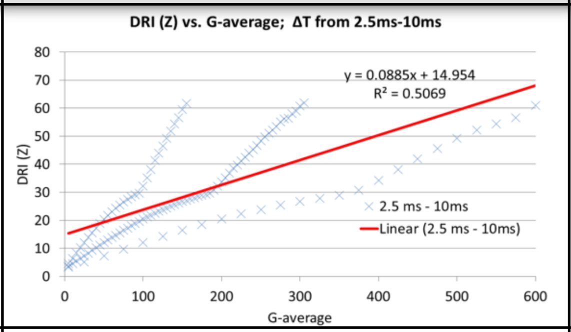
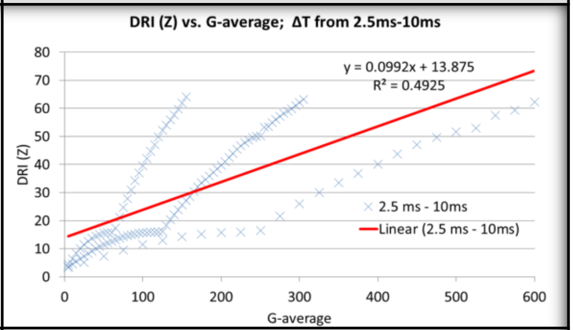
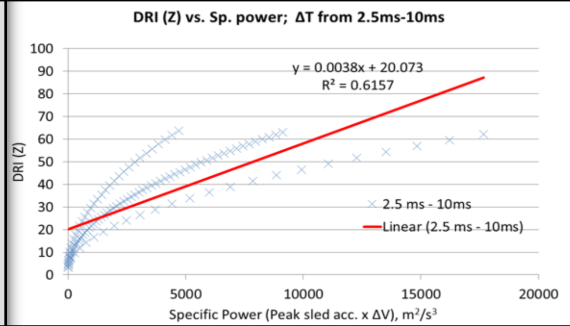
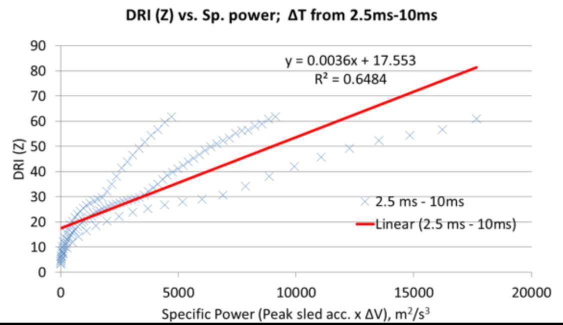
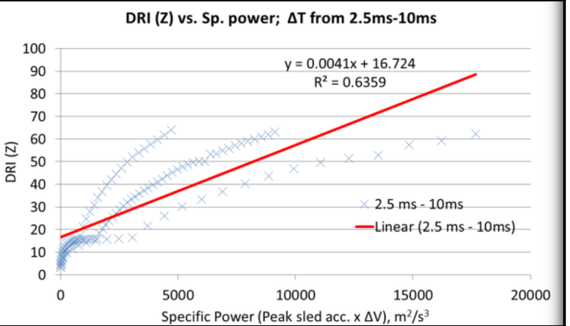
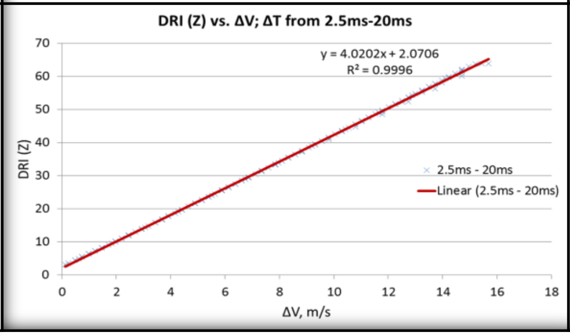
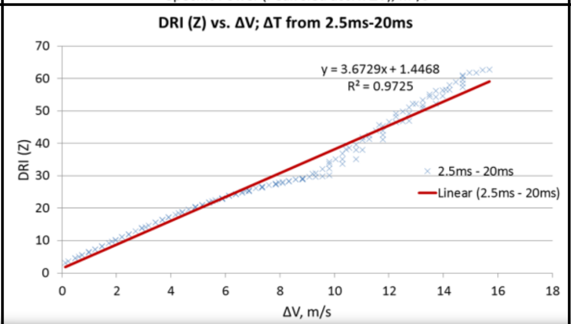
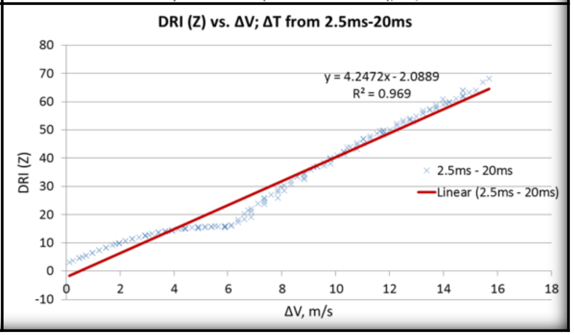
$$r_c = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$

where, x and y are injury criterion and input variable respectively

Head Injury Criteria (HIC_{15}) Trend



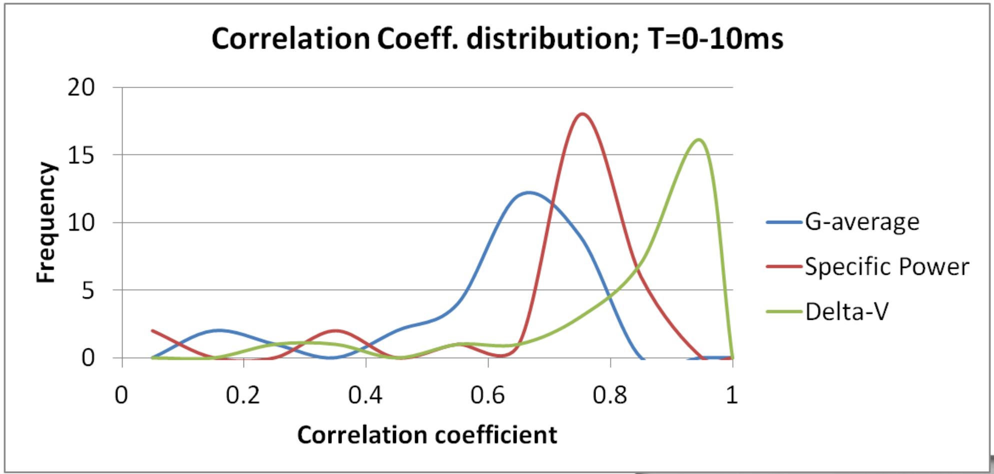
DRI Trend

	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA
Effective-g			
Specific power			
ΔV			

Correlation coeff. (T = 0-10ms)

		Correlation Coefficients								
		T from 0-10ms								
		G-average			Specific power			ΔV		
		Rigid	EA1	EA2	Rigid	EA1	EA2	Rigid	EA1	EA2
1	HIC @15ms	0.67	0.52	0.59	0.81	0.74	0.74	0.94	0.74	0.89
2	Head resultant acceleration @2ms	0.73	0.63	0.65	0.79	0.77	0.77	1.00	0.85	0.96
3	Head resultant acclelaration @0ms	0.73	0.62	0.66	0.78	0.78	0.78	1.00	0.85	0.96
4	Neck injury criteria, N_{ij}	0.71	0.61	0.65	0.79	0.77	0.77	1.00	0.84	0.95
5	Chest resultant acceleration @3ms	0.74	0.63	0.62	0.78	0.74	0.74	0.99	0.87	0.94
6	Chest resultant acceleration @7ms	0.65	0.57	0.73	0.72	0.80	0.80	0.96	0.83	0.95
7	Lumbar spine compression @30ms	0.59	-0.42	0.19	0.53	0.40	0.40	0.77	-0.65	0.30
8	Lumbar spine compression @0ms	-0.75	-0.66	-0.68	-0.80	-0.81	-0.81	-1.00	-0.88	-0.96
9	Pelvis vertical acceleration @7ms	-0.46	-0.23	-0.13	-0.63	-0.08	-0.08	-0.74	-0.58	-0.22
10	DRI (Z)	0.71	0.71	0.70	0.78	0.80	0.80	1.00	0.99	0.99

(pink)	0.5 < r < 0.75
(yellow)	0.75 < r < 0.9
(green)	r > 0.9



Analysis and Observations

Probability of achieving r > 0.8			
	0-10 ms	10 - 20 ms	20 - 60ms
G-Avg	0.00	0.80	0.60
Sp. Pwr	0.20	0.83	0.77
Delta V	0.77	0.83	0.63

For rigid seat only

Probability of achieving r > 0.8			
	0-10 ms	10 - 20 ms	20 - 60ms
G-Avg	0.00	0.90	0.90
Sp. Pwr	0.20	0.90	0.90
Delta V	0.80	0.90	0.80

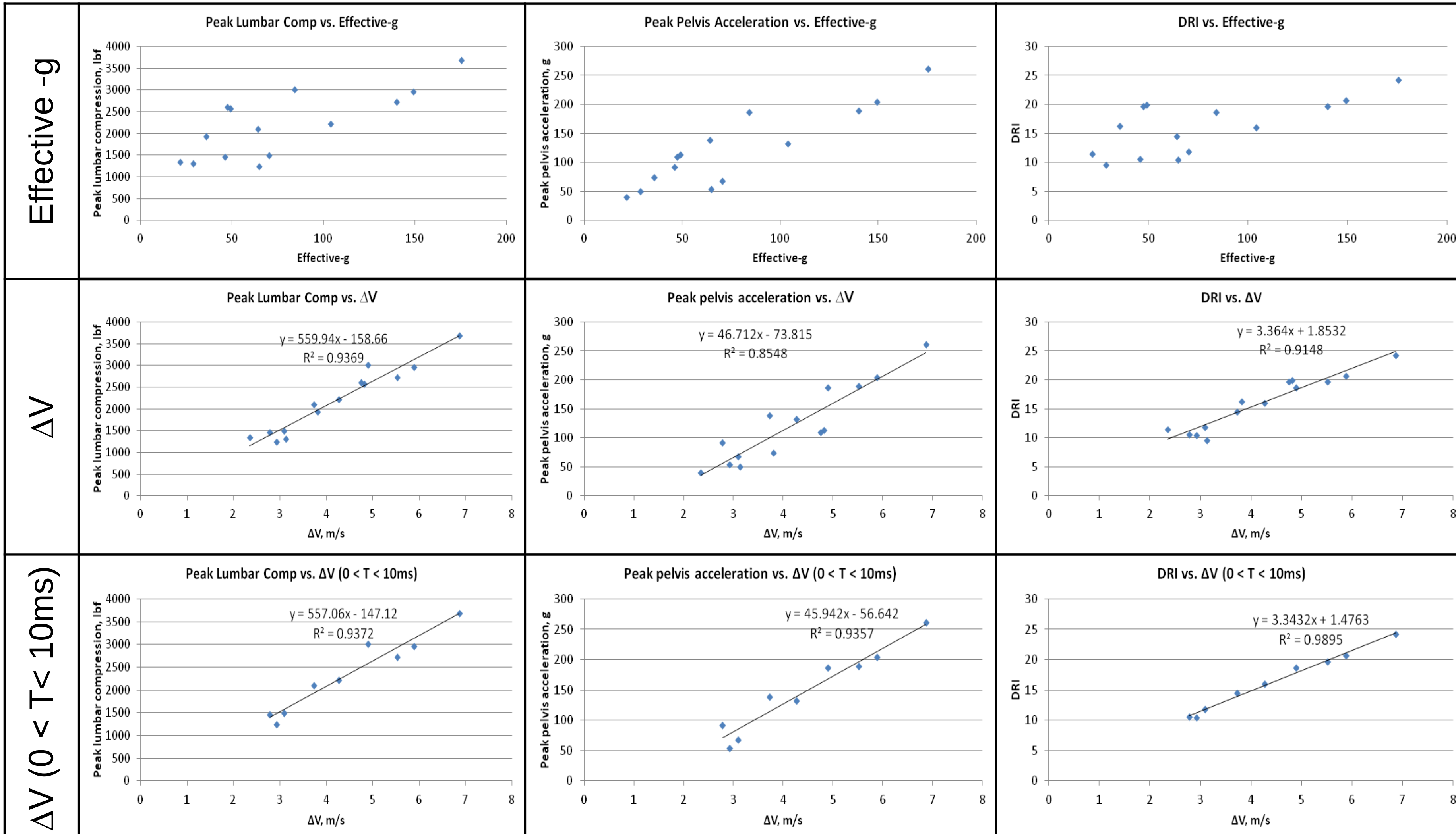
- Among the three loading parameters under consideration, Δv by itself, is a single good indicator in the typical blast loading range of 0-20ms.
- A metamodel is constructed using the results from the parametric study to generate 3d response surfaces for the ten upper body injuries.
- An injury lookup table is constructed based on this parametric study using linear/quadratic regression equations.

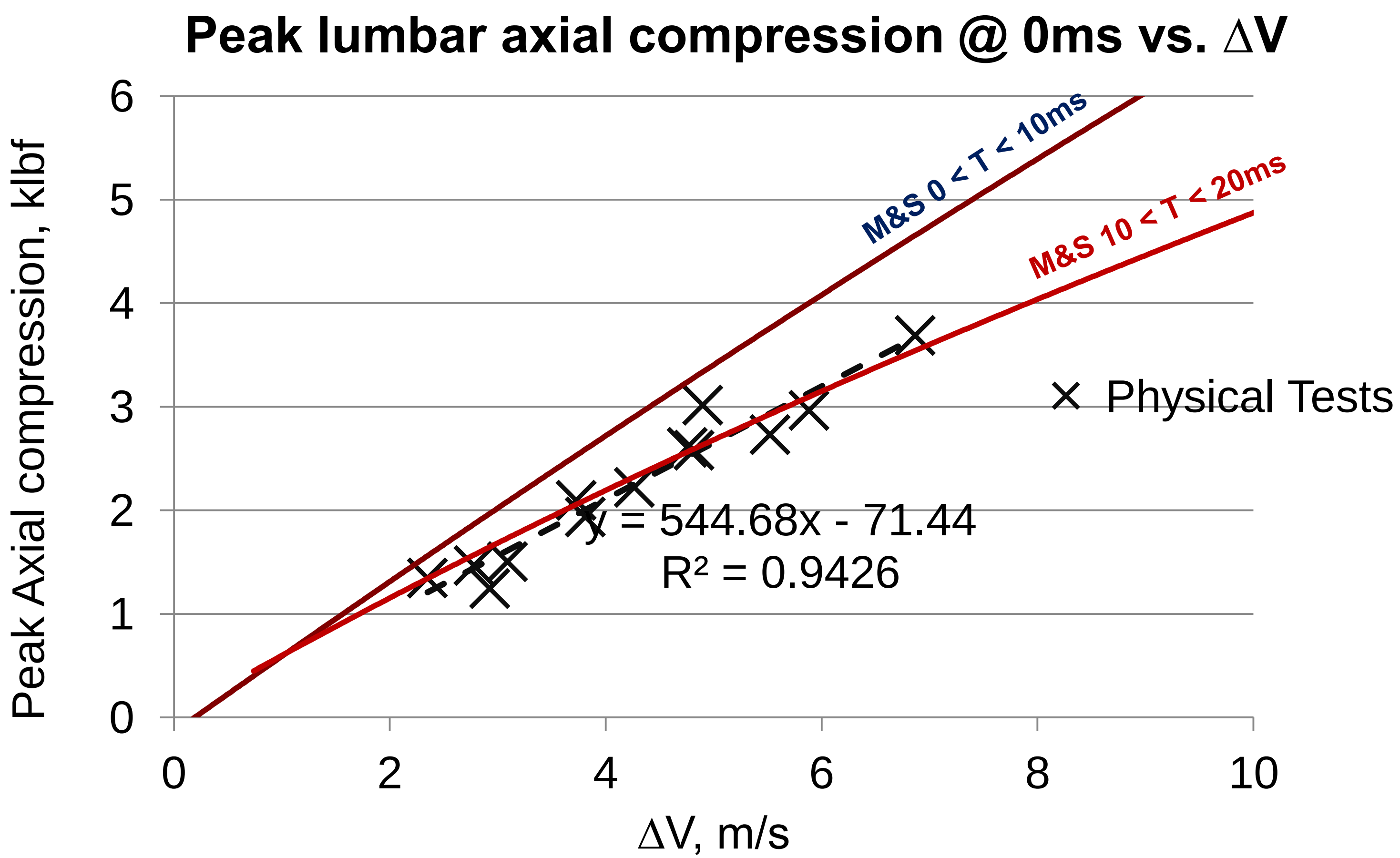
Physical Test data - summary

#	Test	Date	Peak acc., g	ΔV, m/s	0.05% ΔV, m/s	0.95% ΔV, m/s	0.05% T, ms	0.95%T, ms	T, ms	G-avg	Eff-g	Lumbar spine Peak	Lumbar spine 30 ms clip	Pelvic Z acc., g Peak	Pelvic Z acc., g 7 ms clip	DRI
1	5ms-3mps	2/17/2011	93.87	3.09	0.154	2.9353	0.632	4.659	4.43	63	70	1504.1	311.5	67.73	15.41	11.85
2	5ms-3mps-repeat	2/18/2011	87.10	2.93	0.146	2.7790	0.729	4.861	4.55	60	65	1244.7	180.9	54.38	19.97	10.45
3	5ms-4mps	2/17/2011	139.48	4.26	0.213	4.0516	0.686	4.446	4.14	87	104	2221.4	312.8	131.91	12.91	16.07
4	5ms-6mps	2/18/2011	189.00	5.52	0.276	5.2453	0.519	4.134	3.98	113	140	2730.5	205.2	189.24	8.14	19.7
5	5ms-6msp-repeat	2/18/2011	201.69	5.88	0.294	5.5883	0.548	4.162	3.98	120	149	2965.1	234.1	204.14	5.48	20.7
6	5ms-7mps	2/18/2011	237.72	6.87	0.343	6.5228	0.545	4.132	3.95	140	176	3688.4	214.9	260.74	5.81	24.29
7	20ms-3mps	2/17/2011	27.79	2.35	0.117	2.2310	0.663	10.592	10.92	48	22	1345.9	325.8	39.72	23.77	11.45
8	20ms-4mps	2/17/2011	47.80	3.81	0.191	3.6198	1.110	10.878	10.74	78	36	1935.7	374.8	74.27	25.23	16.27
9	20ms-5mps	2/17/2011	68.07	4.82	0.241	4.5764	1.275	10.262	9.89	98	49	2580.3	375.2	113.24	22.6	19.92
10	20ms-5mps-repeat	2/17/2011	65.60	4.75	0.238	4.5172	1.317	10.503	10.10	97	47	2607.1	402.1	110.3	20.44	19.68
11	5ms-10in	NA	74.25	2.78	0.139	2.6403	0.411	5.953	6.10	57	46	1466.7	200.1	91.61	4.41	10.65
12	5ms-19in	NA	112.04	3.73	0.186	3.5397	0.391	5.721	5.86	76	64	2096.3	200.2	138.97	4.74	14.52
13	5ms-30in	NA	156.53	4.90	0.245	4.6537	0.384	5.726	5.88	100	84	3015.4	171.9	187.05	5.17	18.63

	Peak Acc., g	ΔV, m/s	T, ms
Minimum	28	2.3	3.95
Maximum	238	6.9	11.04
Mean	111	4.2	6.83

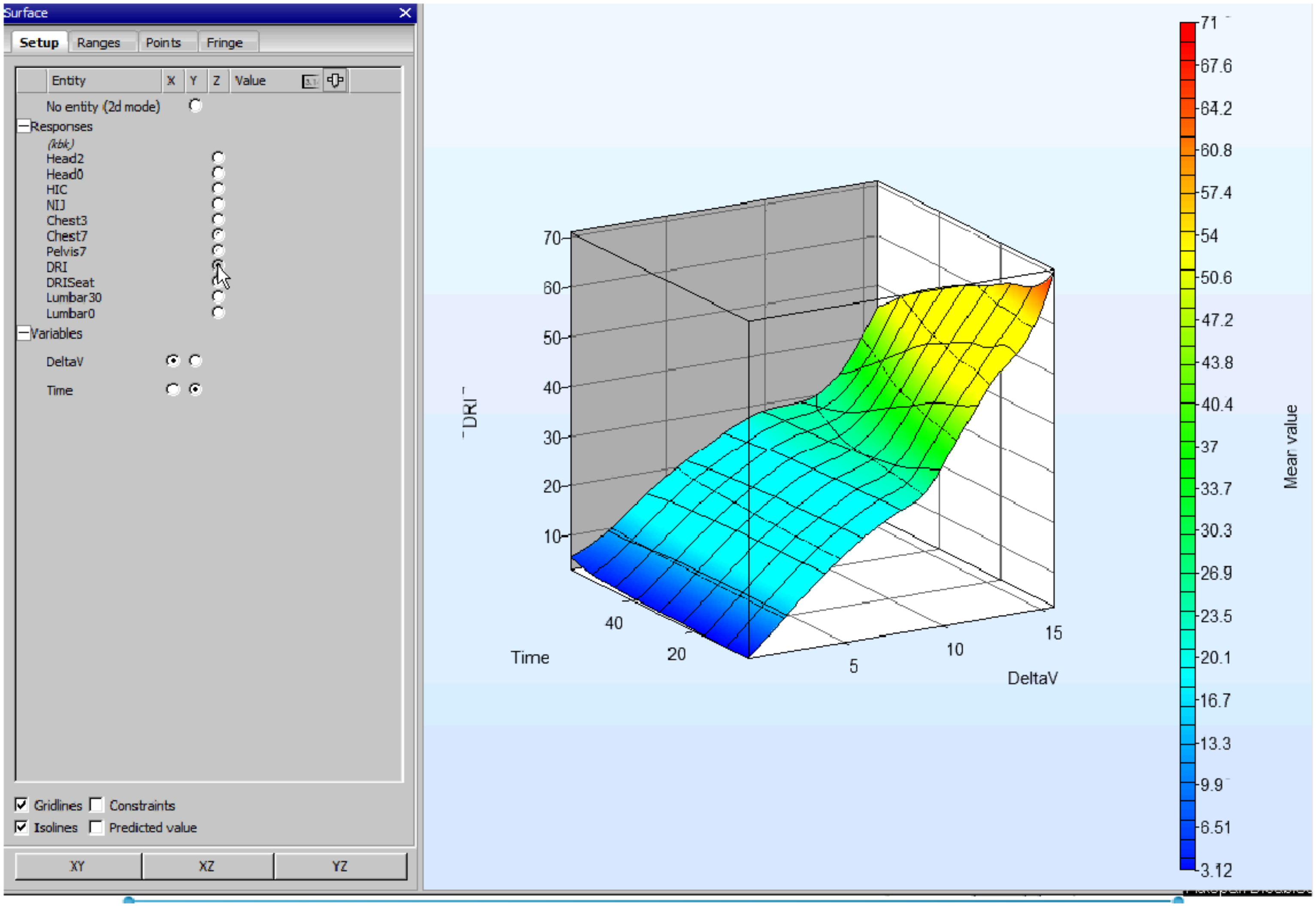
Physical Test data



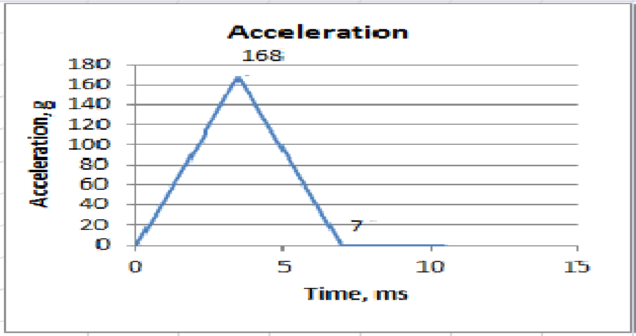


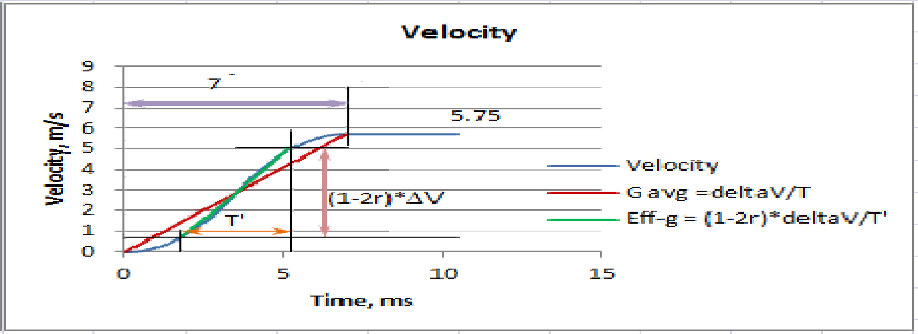
A linear trend line can be seen injury data ($0 \le T \le 20$ms) from physical tests

Injury lookup charts (Response Surface)



Injury lookup tool





#	Blast load parameters	Value
1	Peak accleleration, G_{peak}	168
2	Time duration of pulse, T, ms	7
3	"r" factor, % (default 5%)	12
4	ΔV, m/s	**5.77**
5	Adjusted ΔV for effective-g	4.4
6	Adjusted time for effective-g	3.48
7	G-Average	84
8	Effective-g	125

#	Occupant Injury Criteria		Seat EA system		
	Criteria	Reference values	None	OCP (15kN)	OCP (7.5 kN)
1	HIC @15ms	350, 700, 1050 (Low, moderate, high risk)	232	71	10
2	Head resultant acceleration (2ms clip	150g	75.9	37.3	24.4
3	Head resultant acclelaration (Peak)	180g	81.1	39.6	25.7
4	Neck injury criteria, Nij	<1	0.65	0.28	0.18
5	Chest resultant acceleration (3ms clip	60g	78.7	34.0	22.8
6	Lumbar spine compression (Peak)	6672 N	-17,408	-7,164	-5,514
7	DRI_z	15, 18, 23 (low, moderate, high risk)	25	23	18

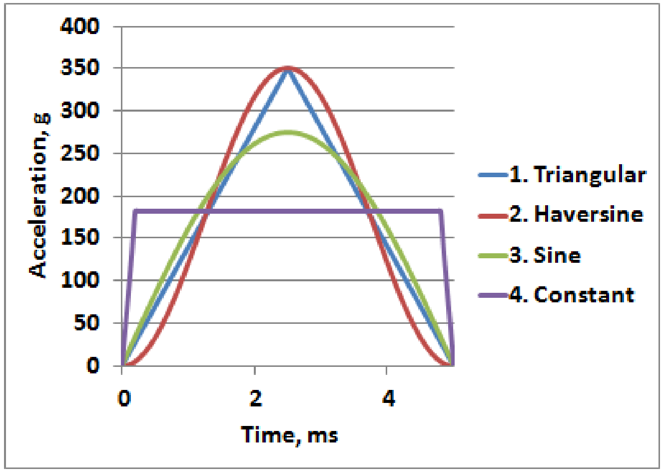
Effect of loading paths

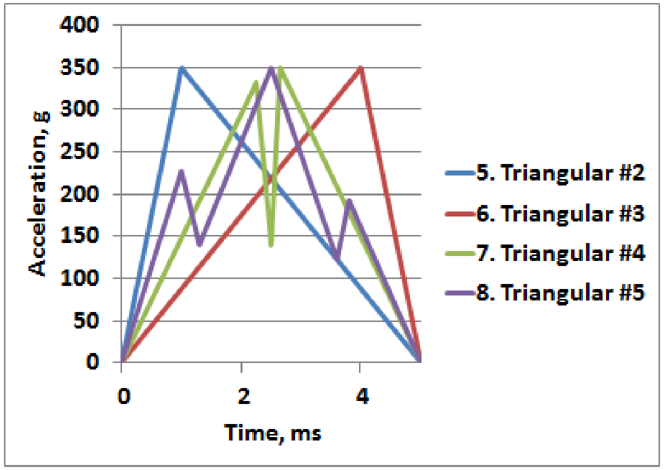
A typical blast pulse is modified such that every pulse yielded the same final velocity, ΔV of 8.6 m/s within the same time duration of 5 ms; i.e., same G-average of 175g

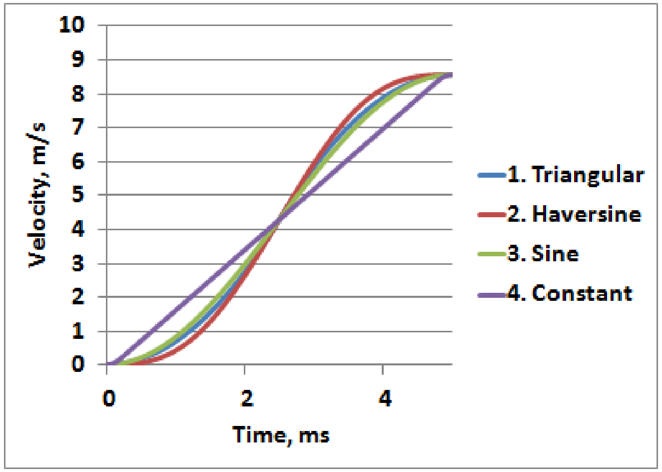
The eight pulses are;

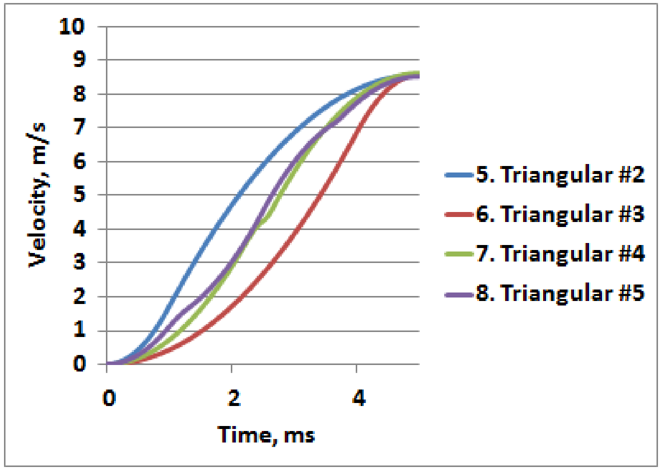
1. Typical triangular
2. Haversine
3. Sine (Scaled by π/4)
4. Constant
5. Front loaded triangular (#2)
6. Rear loaded triangular (#3)
7. Triangular with two peaks (#4)
8. Triangular with three peaks (#5)

The analysis also repeated for a second set of pulses with 10ms duration keeping the final velocity at 8.6m/s (G-average of 87.5g)









Effect of loading paths (T = 5ms)

T = 5ms

Pulse iterations									HEAD			NECK	CHEST		PELVIS		LUMBAR SPINE	
									Resultant acceleration, g		HIC	N_{ij}	Resultant acceleration, g		Z-Acceleration, g	DRI (z), g	Axial compression, kN	
#	Pulse type	Peak, Dec., g	Duration, ms	Rate of onset, g/ms	ΔV, m/s	Sp. Pwr	Eff. G	G-avg	@ 2ms	@ 0ms	@ 15 ms	CFC 1000	@ 3ms	@ 7ms	@ 7ms		@30ms	@0ms
1	Triangular	350	5	140	8.6	3004	218	175	113.4	122.7	687	0.96	111.2	33.9	-4.9	36.4	0.0	-26.5
2	Haversine	350	5	140	8.6	3003	235	175	113.6	122.9	689	0.96	111.7	34.9	-4.8	36.4	0.0	-26.5
3	Sine	275	5	110	8.6	2360	210	175	113.2	122.5	679	0.96	110.7	32.6	-4.8	36.2	0.0	-26.4
4	Constant	182	5	NA	8.6	1562	181	175	112.5	121.5	673	0.96	109.1	30.5	-4.9	36.3	0.0	-26.3
5	Triangular #2	350	5	140	8.6	3004	212	175	113.8	123.1	689	0.97	111.3	33.8	-4.9	36.4	0.0	-26.5
6	Triangular #3	350	5	140	8.6	3004	212	175	112.9	122.1	683	0.96	110.6	32.7	-4.9	36.4	0.0	-26.4
7	Triangular #4	350	5	140	8.6	3004	217	175	114.0	123.4	701	0.97	111.7	33.8	-5.0	36.6	0.0	-26.6
8	Triangular #5	350	5	140	8.6	3004	205	175	112.9	122.1	673	0.96	110.3	33.0	-4.9	36.2	0.0	-26.3

Including "Constant" type pulse

Mean, μ =	8.6	2743	211.2	175.0	113.3	122.5	684.3	1.0	110.8	33.2	-4.9	36.4	0.0	-26.4
Standard deviation, σ =	0.0	528	15.1	0.0	0.5	0.6	9.4	0.0	0.9	1.3	0.1	0.1	0.0	0.1
Coefficient of variation, C_v (%)	0%	19%	7%	0%	**0%**	**1%**	**1%**	**0%**	**1%**	**4%**	**1%**	**0%**	**0%**	**0%**

Excluding "Constant" type pulse

Mean, μ =	8.6	2912.0	215.4	175.0	113.4	122.7	685.9	1.0	111.1	33.5	-4.9	36.4	0.0	-26.5
Standard deviation, σ =	0.0	243.6	9.8	0.0	0.4	0.5	8.9	0.0	0.5	0.8	0.1	0.1	0.0	0.1
Coefficient of variation, C_v (%)	0%	8%	5%	0%	**0%**	**0%**	**1%**	**1%**	**0%**	**2%**	**1%**	**0%**	**0%**	**0%**

No path dependency of loading is observed

Conclusions

- There is no single blast loading parameter from an input pulse which can be used to fully determine the occupant injury risk from a blast loading over a wide range of pulse durations (0-60ms).
- Correlation coefficients distribution for Δv especially in the 0-10ms range is narrower and closer to 1 than those for Specific Power and Effective-g.
- Among the different blast pulse parameters considered in this study, Δv is the best single indicator for estimating injury criteria, for typical blast pulse duration ranges.
- Two different approaches to estimate occupant injuries as a function of Blast duration, Δv, and Seat characteristics have been employed using the results from this parametric study, namely:
  - **Injury lookup tables using linear/quadratic regression equations**
  - **Meta-model based Response surface methodology**
- Other:
  - **For any given Δv and T (0-10ms), the shape of the pulse and its peak value has no significant effect on the injury criteria (excluding the constant type)**
  - **Trends in the test data strongly support M&S findings of this study.**

References

1. "*Application of mathematical modeling in potentially survivable blast threats in military vehicles*" - Sudhakar Arepally, Dr. David Gorsich, Karrie Hope, Stephen Gentner and Kari Dortleff - 26th Army Science Conference, 1-4 December 2008, Orlando, Florida, United States
2. "*Response of dummies to high onset rate G_z loading on sled*" – Nagarajan Rangarajan, Jason Moore, Paul Gromowski, James Rinaldi, Narayan Yoganandan, Frank Pintar, Dennis Mariman and B Joseph McEntire – Personal Armor Systems Symposium (PASS 2012), 17-21 September 2012, Nuremberg, Germany
3. "*Crew Injury Risk Assessment – Effective g vs. Delta V*" – James Sheng and Sudhakar Arepally – Undated TARDEC Brief

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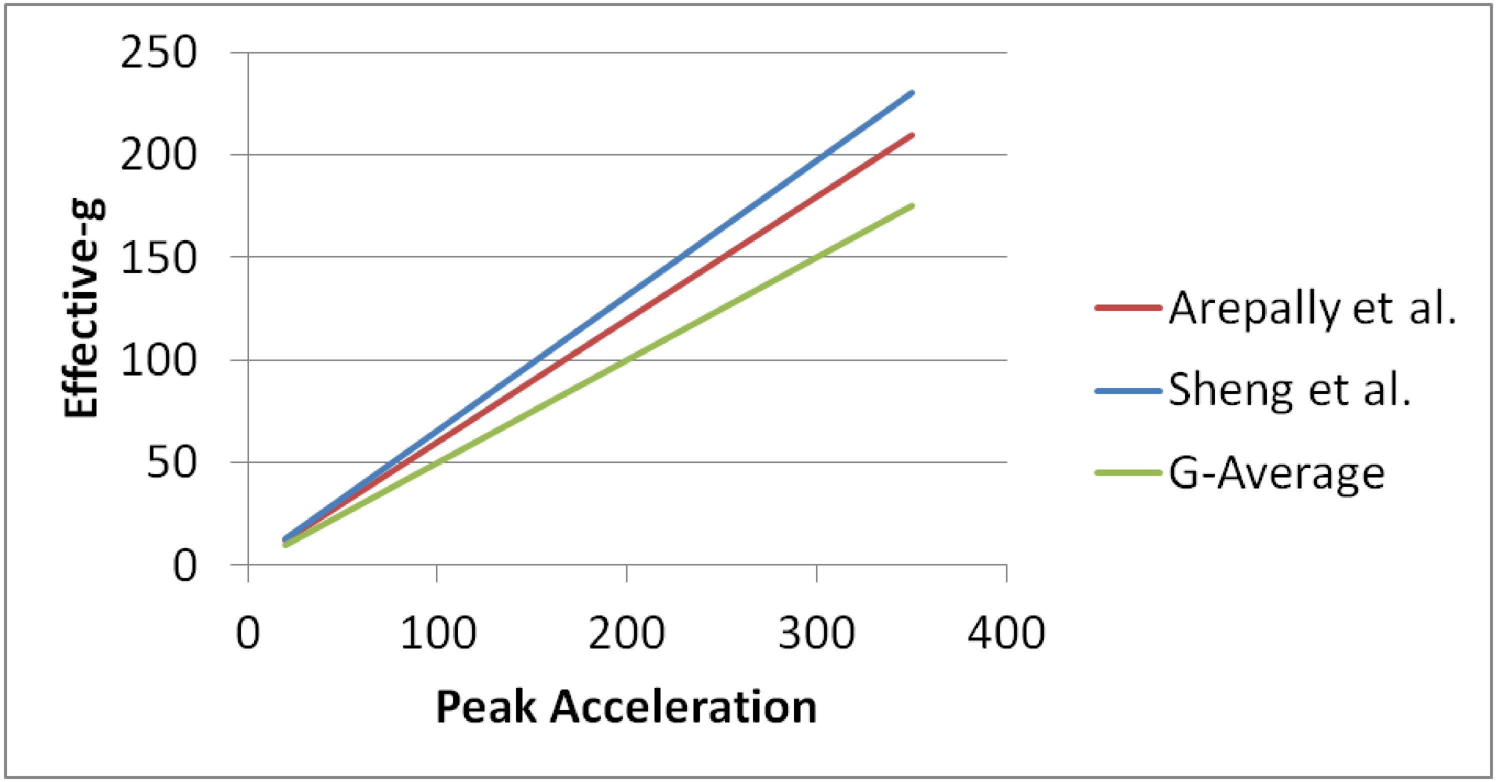
The authors are also most grateful to Mr. Sudhakar Arepally for his reviews of this work, and for patiently providing insight to his earlier research on Effective-G [13], which served as the precursor for this project.

BACKUP SLIDES

For triangular shaped pulses studied;

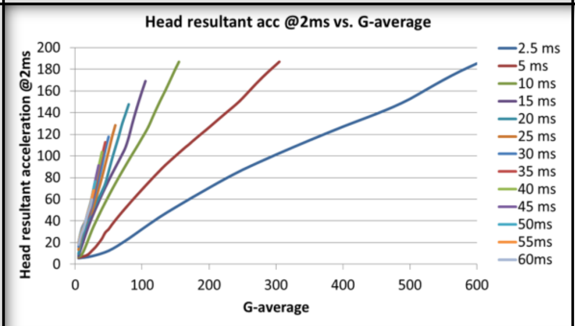
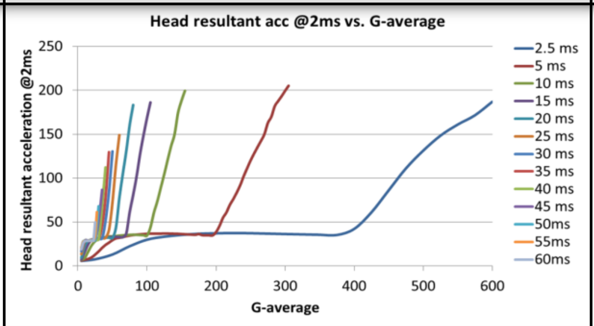
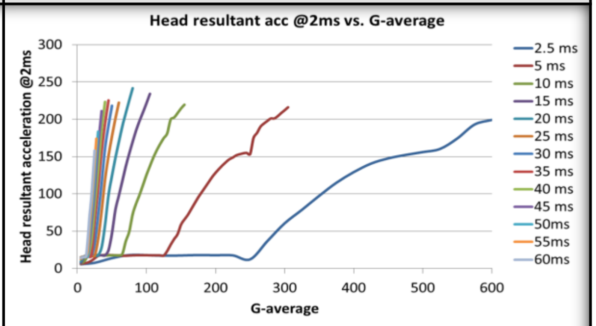
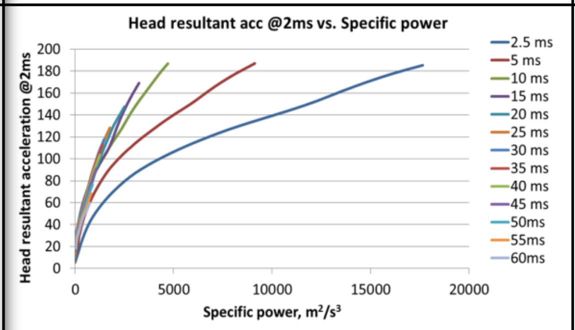
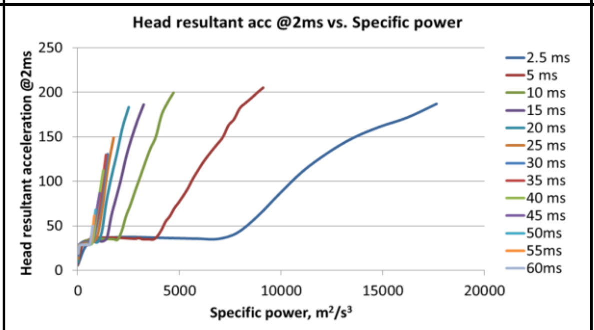
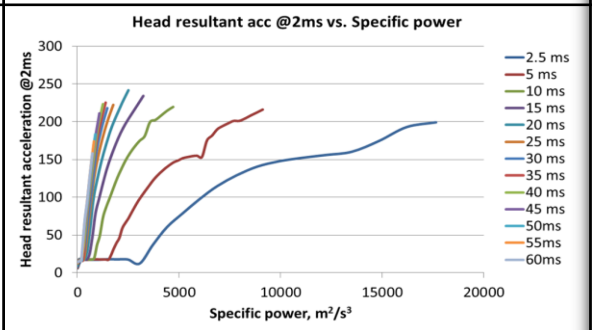
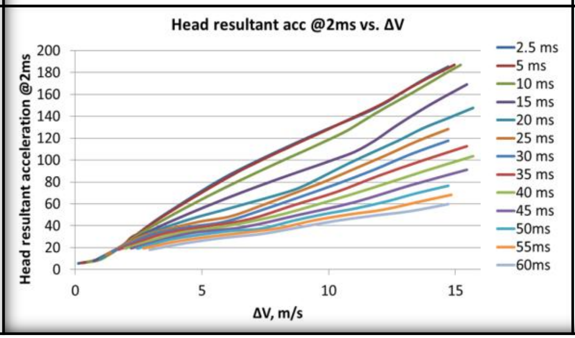
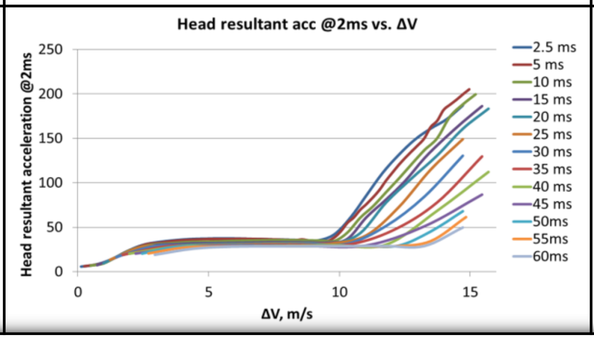
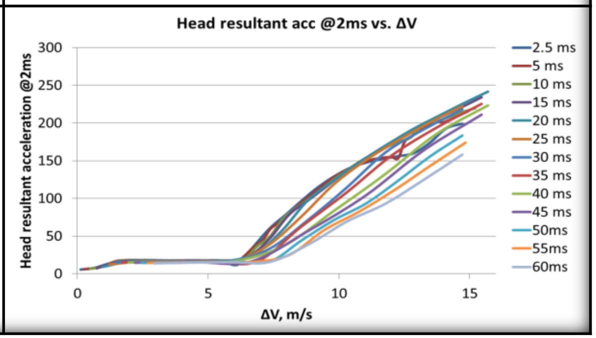


G_{eff} (Arepally et. al.) $= 0.6 * G_{peak}$

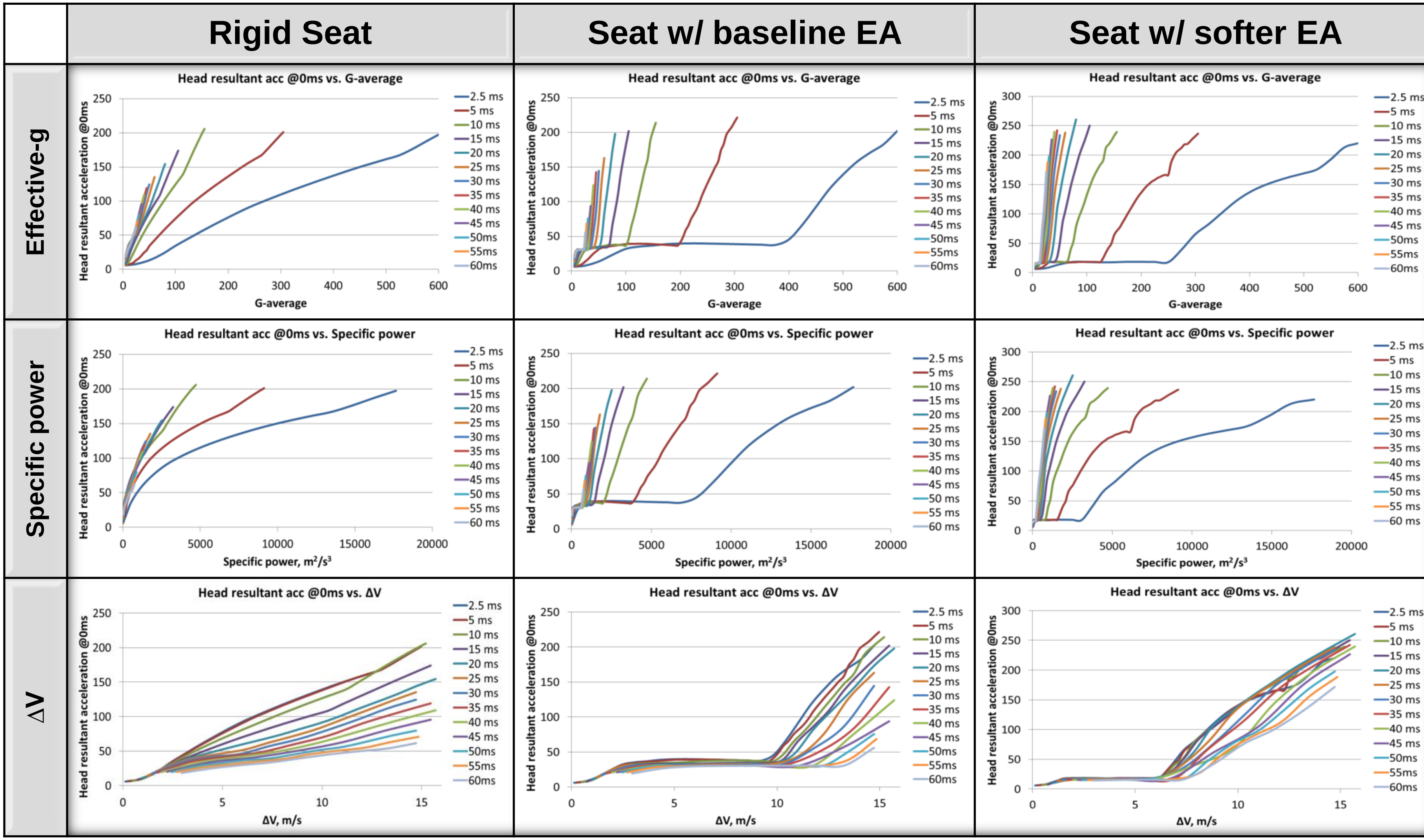
G_{eff} (Sheng et. al.) $= 0.6581 * G_{peak}$ (when r=0.05)

$G_{avg} = 0.5 * G_{peak}$

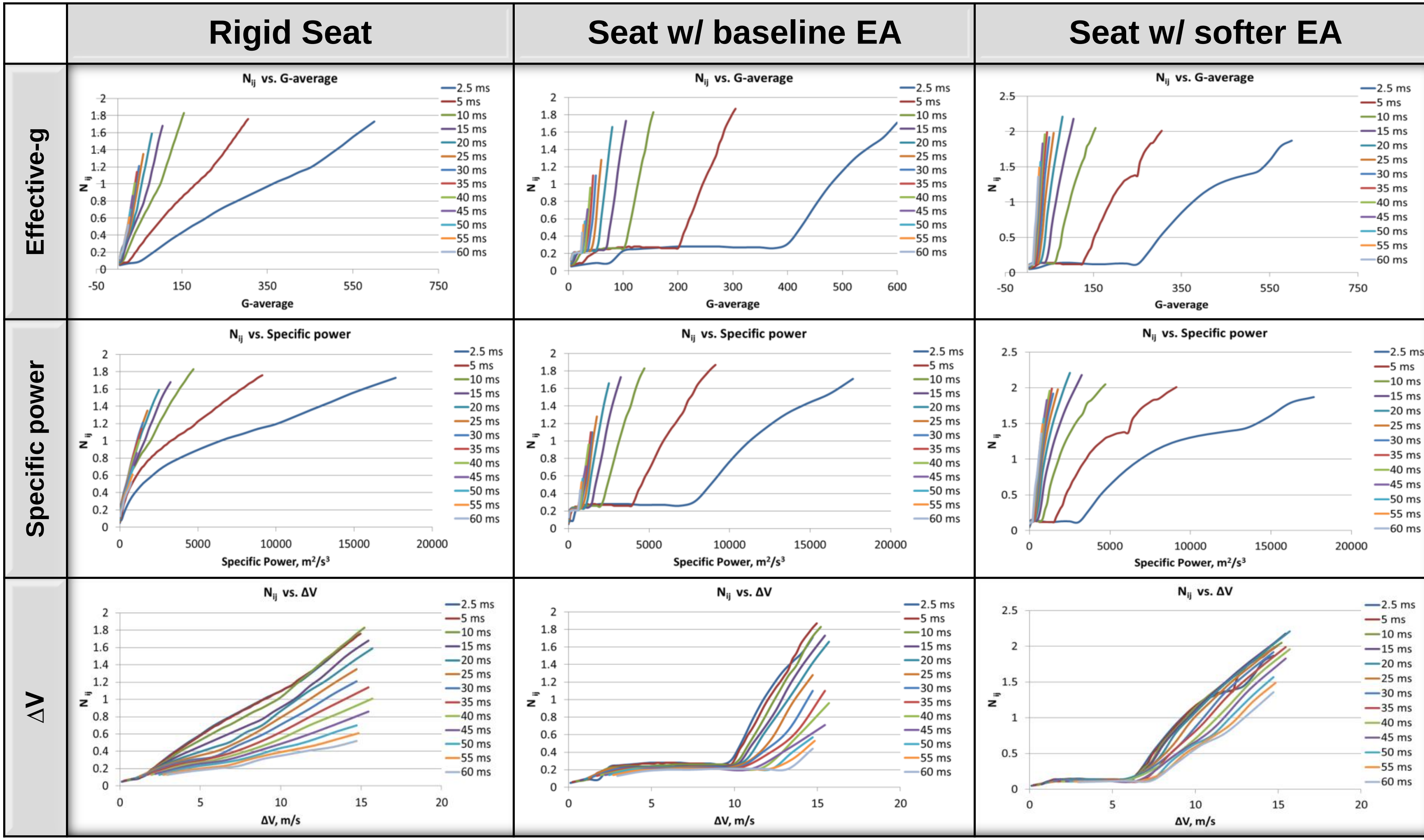
Head resultant acceleration (2ms-clip)

	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA
Effective-g			
Specific power			
ΔV			

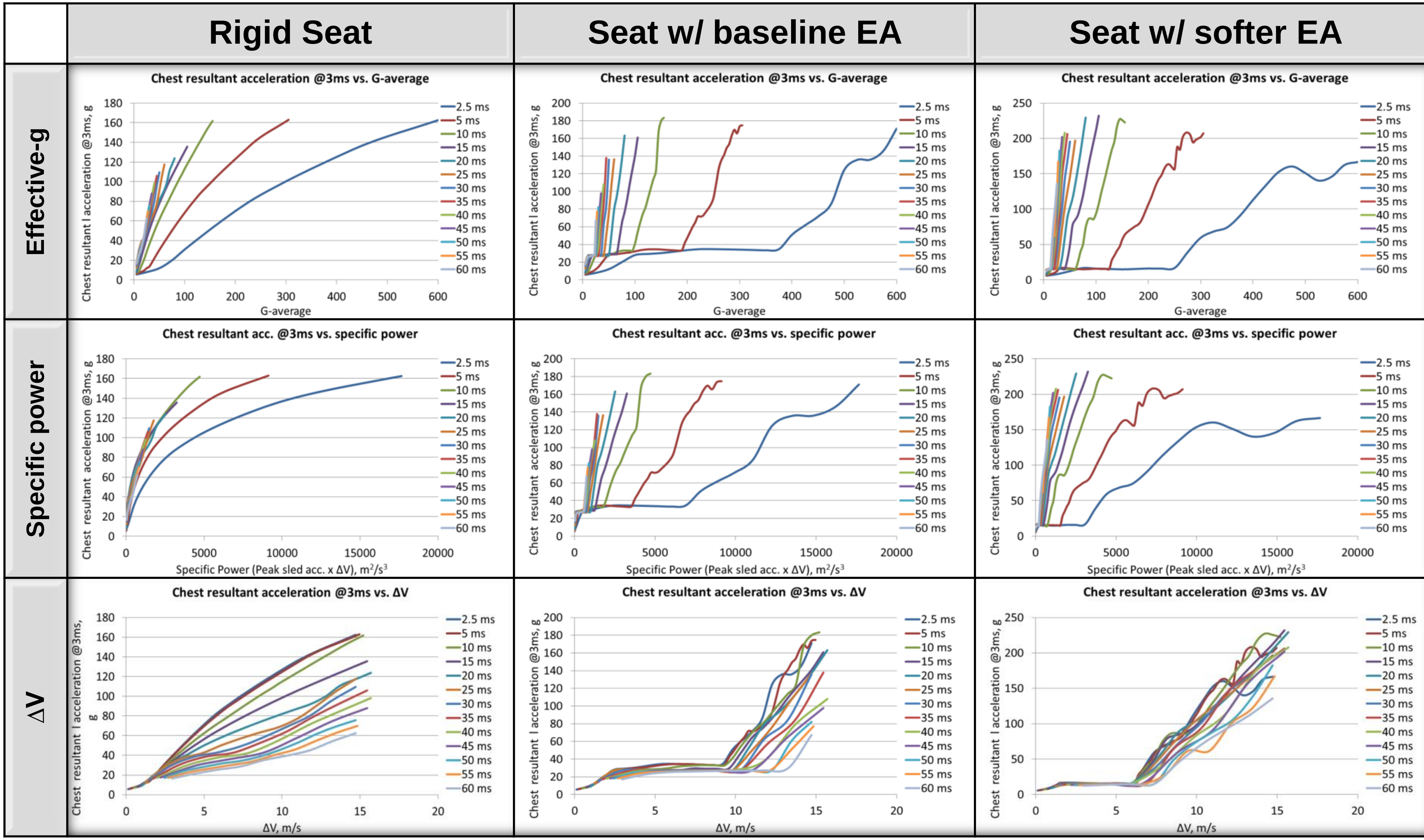
Head resultant acceleration (Peak)



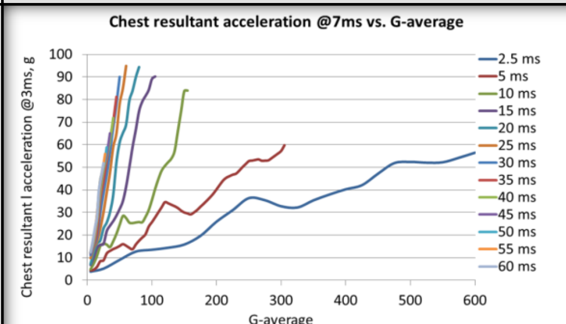
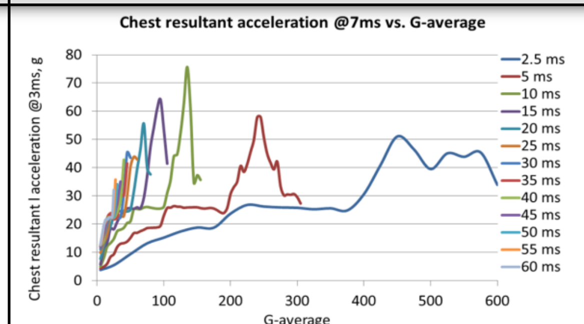
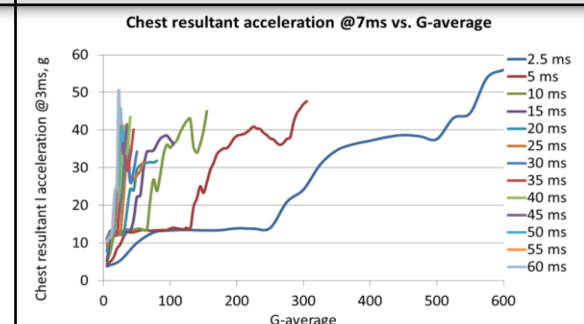
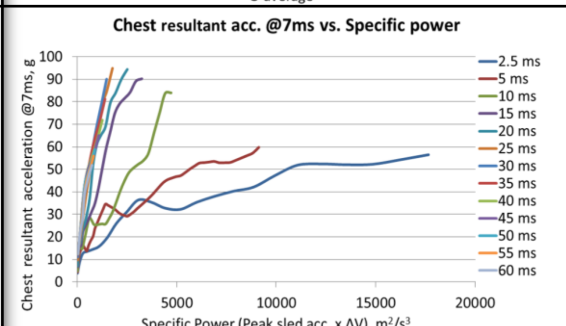
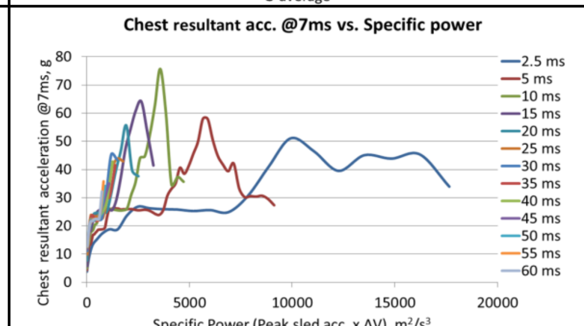
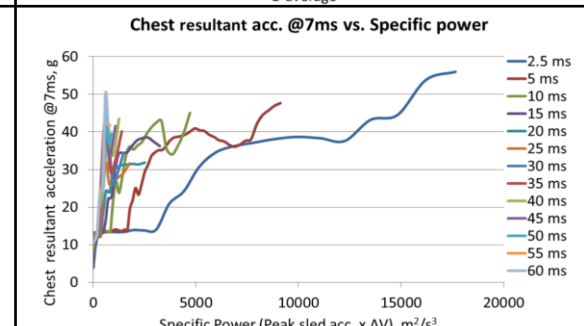
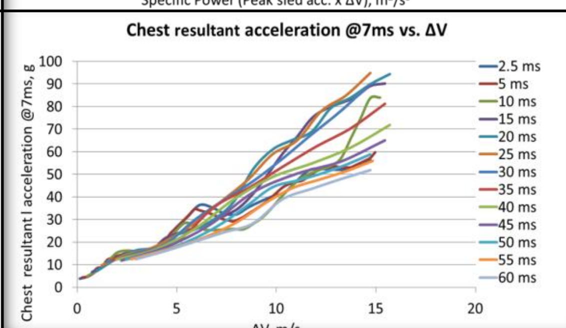
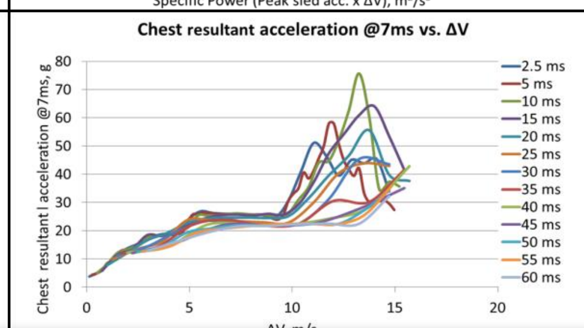
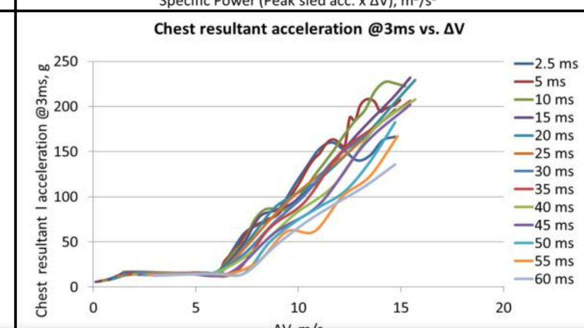
Neck injury criteria N_{ij}



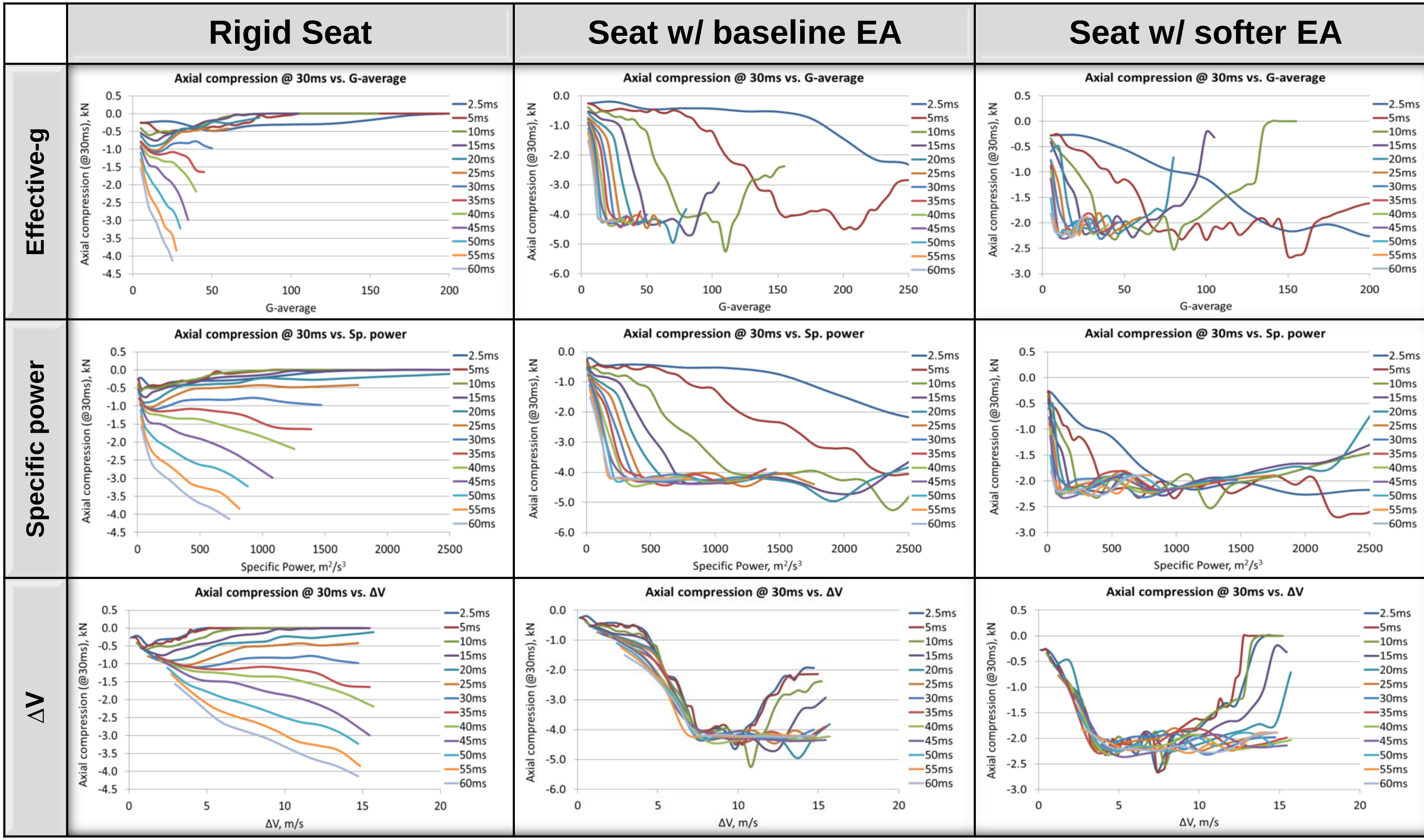
Chest resultant acceleration (3ms-clip)



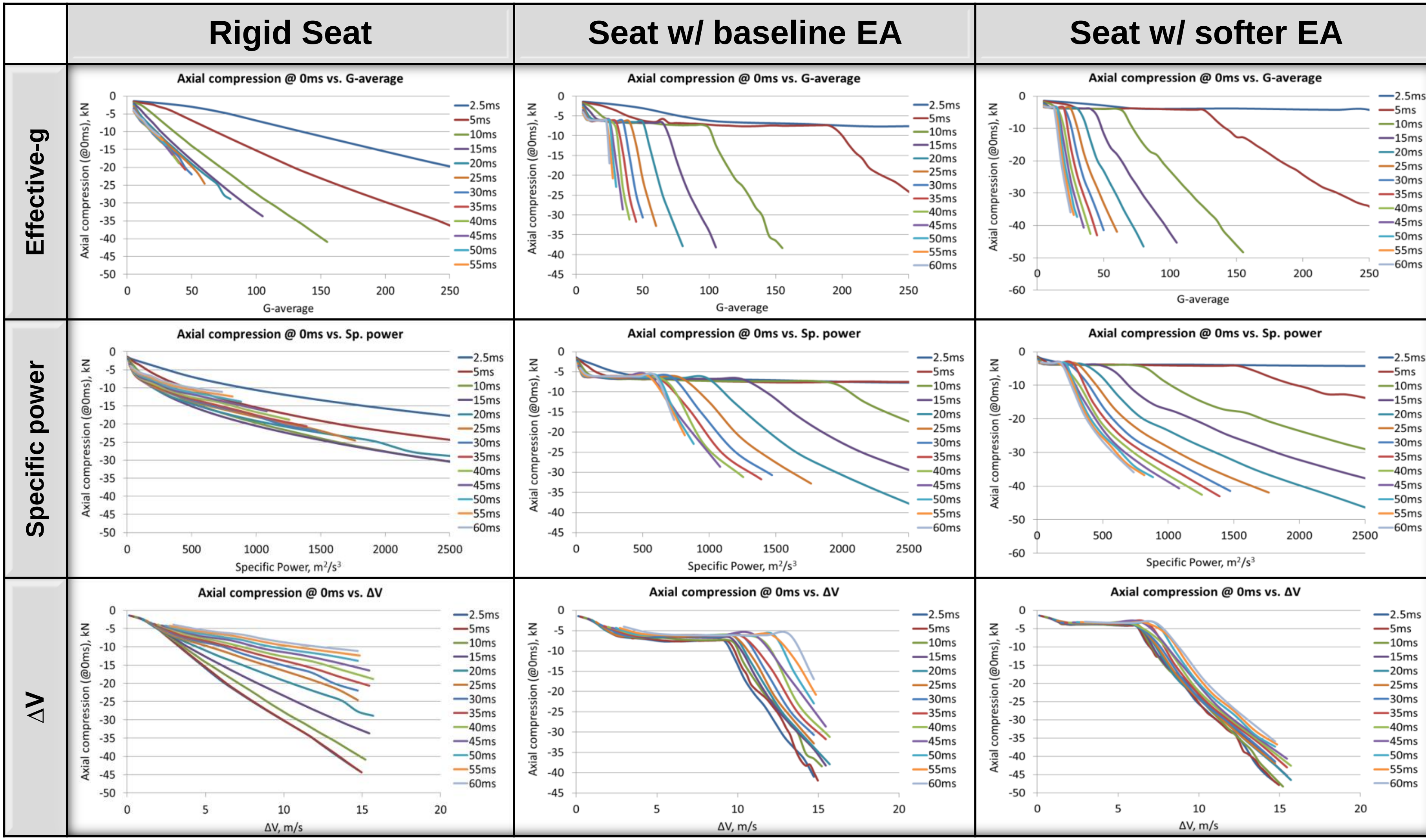
Chest resultant acceleration (7ms-clip)

	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA
Effective-g			
Specific power			
ΔV			

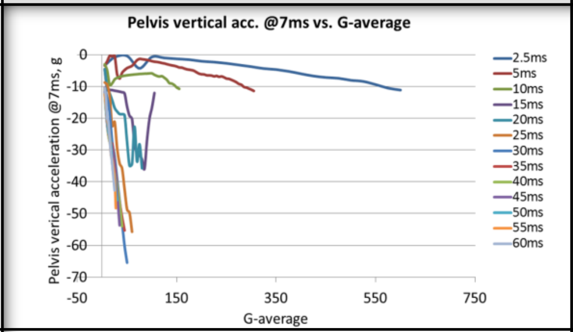
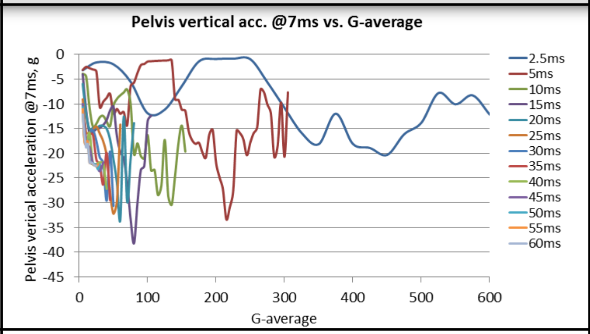
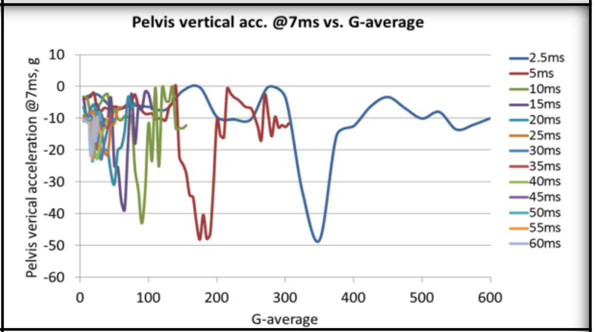
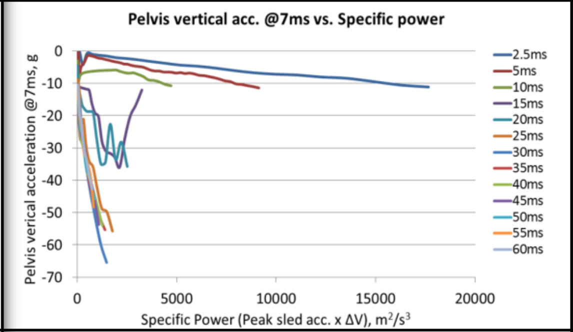
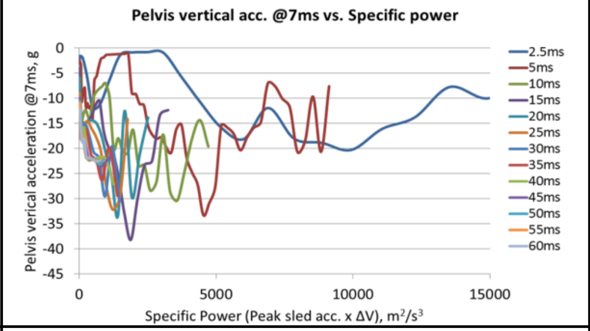
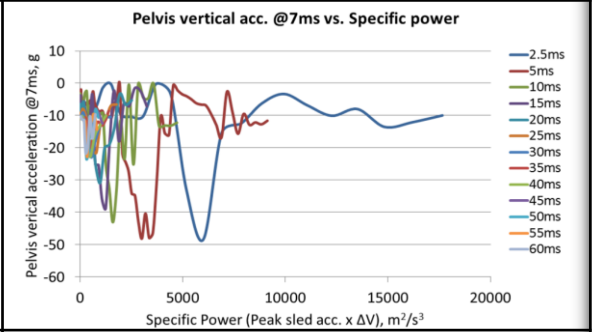
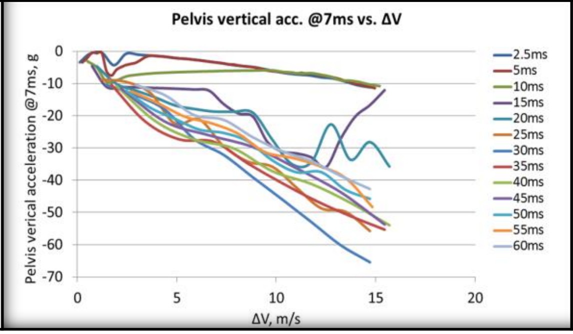
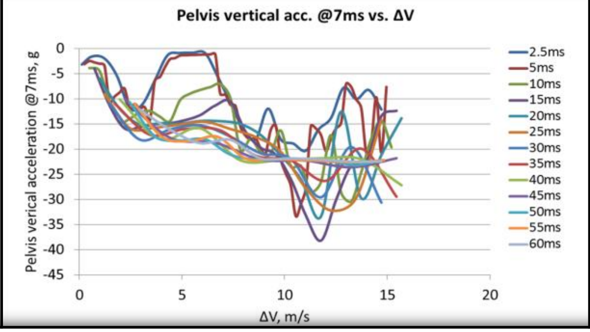
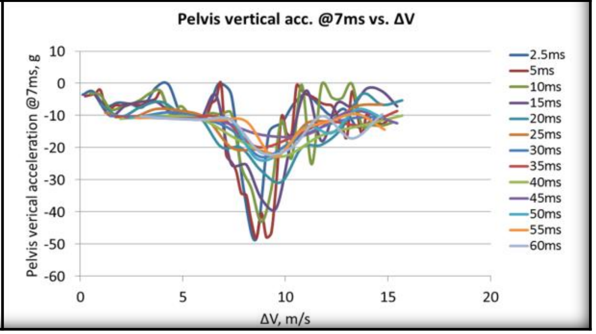
Lumbar compression (30ms-clip)



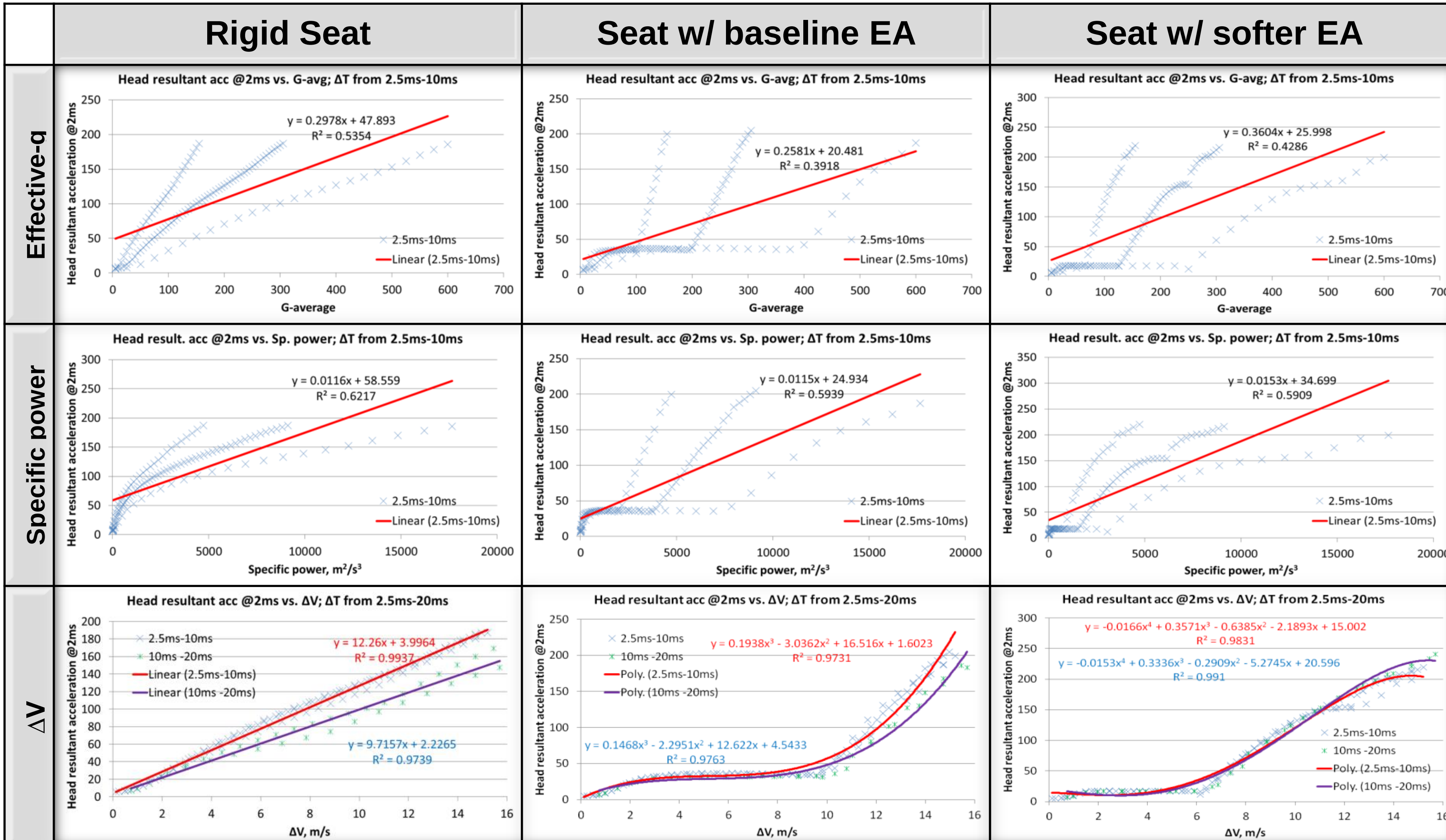
Lumbar compression (Peak)



Pelvis vertical acceleration (7ms-clip)

	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA
Effective-g			
Specific power			
ΔV			

Head resultant acc. (2ms-clip) Trend

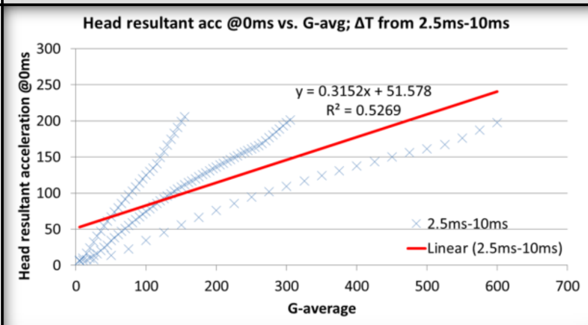


Blast load descriptors as occupant injury predictors for underbody blast events

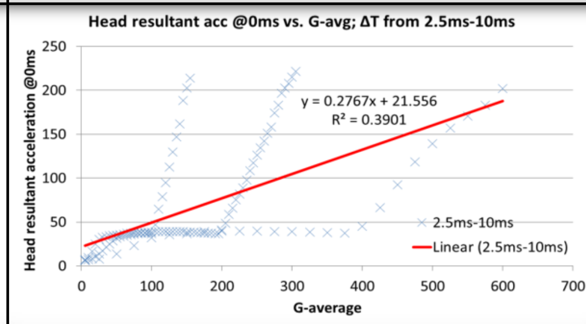
Head resultant acc. (Peak) Trend

Effective q

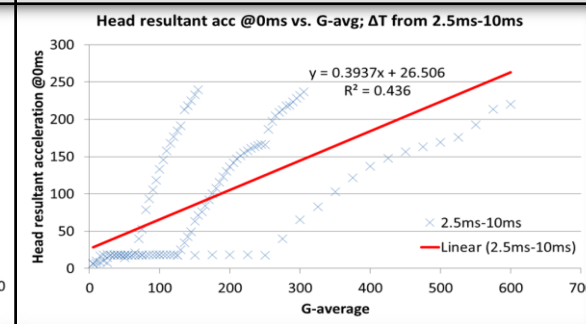
Rigid Seat



Seat w/ baseline EA

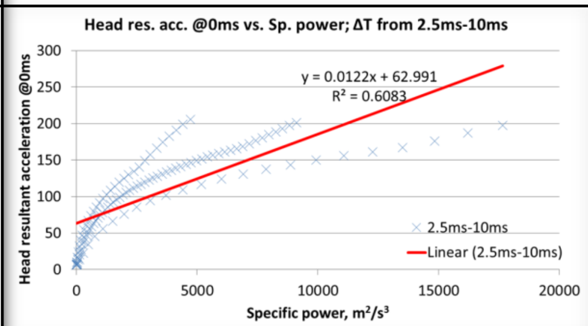


Seat w/ softer EA

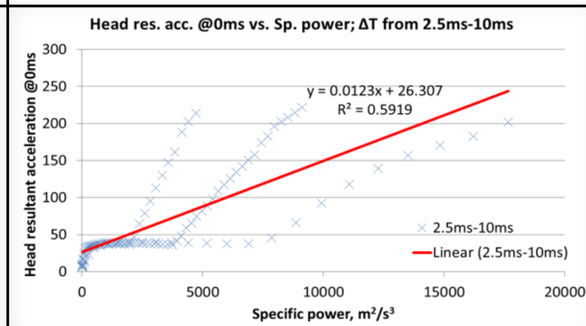


Specific power

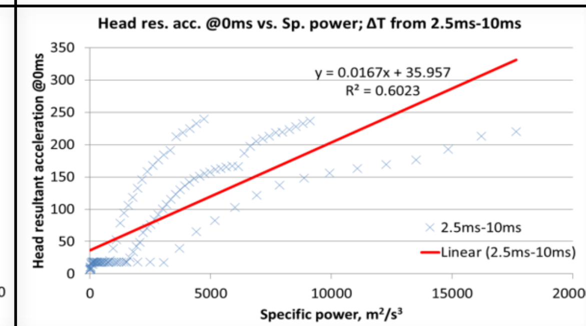
Rigid Seat



Seat w/ baseline EA

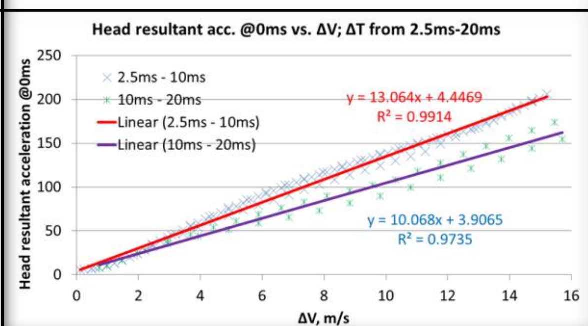


Seat w/ softer EA

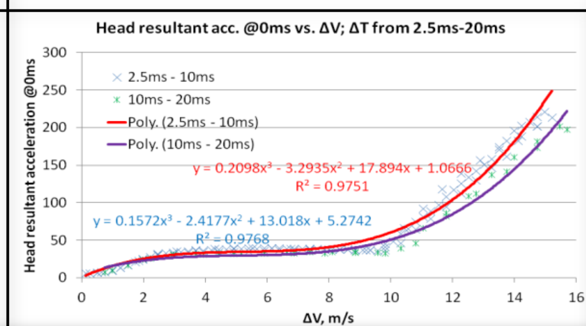


ΔV

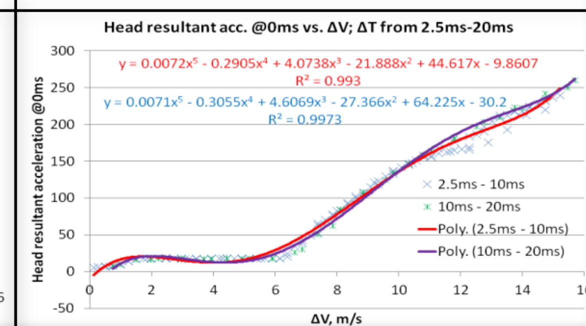
Rigid Seat



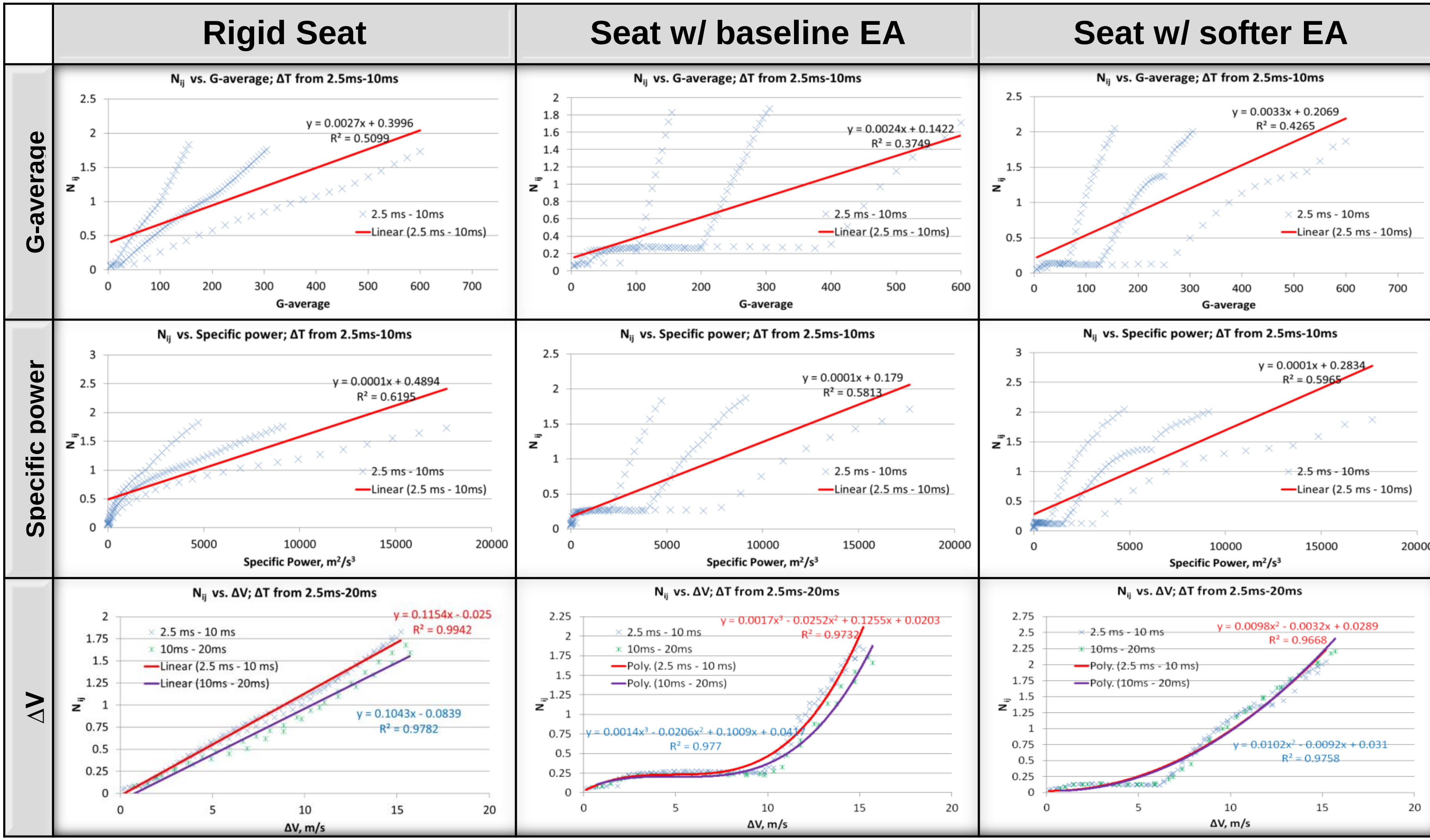
Seat w/ baseline EA



Seat w/ softer EA



Neck injury criteria N_{ij} (Trend)

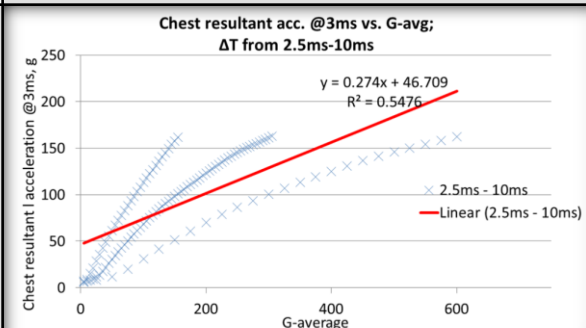


Chest resultant acc. (3ms-clip) Trend

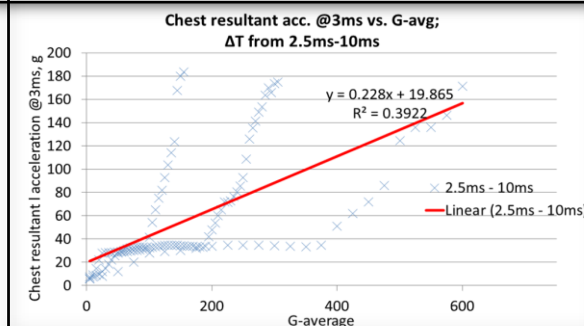
Columns: Rigid Seat | Seat w/ baseline EA | Seat w/ softer EA

Effective g

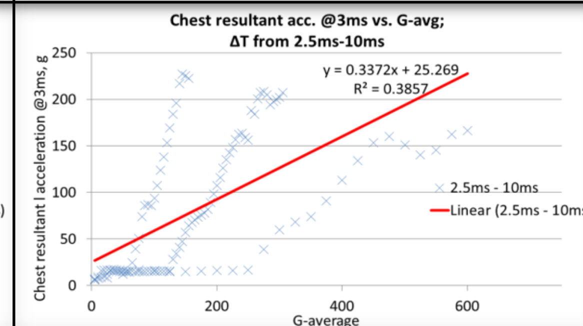
Rigid Seat



Seat w/ baseline EA

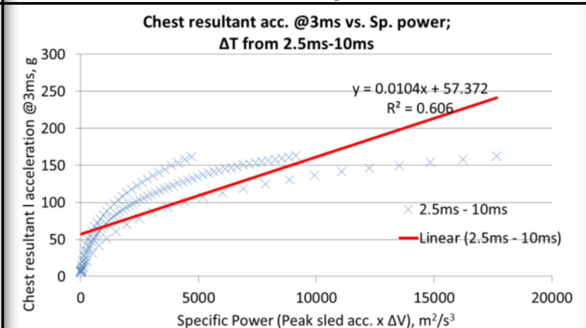


Seat w/ softer EA

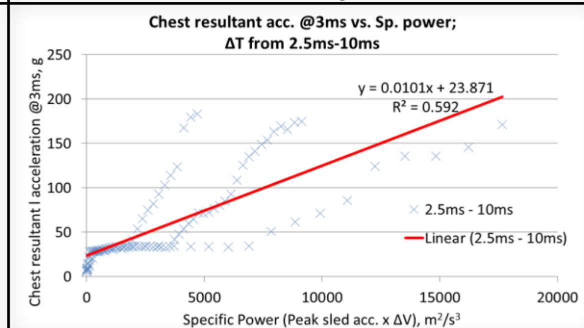


Specific power

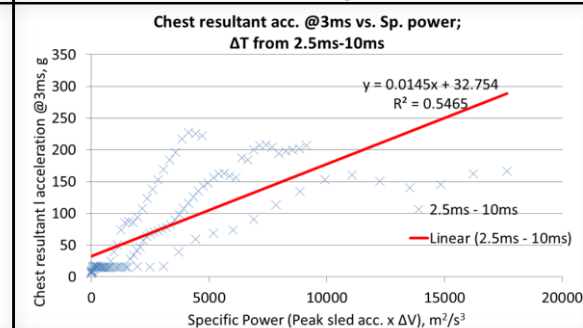
Rigid Seat



Seat w/ baseline EA

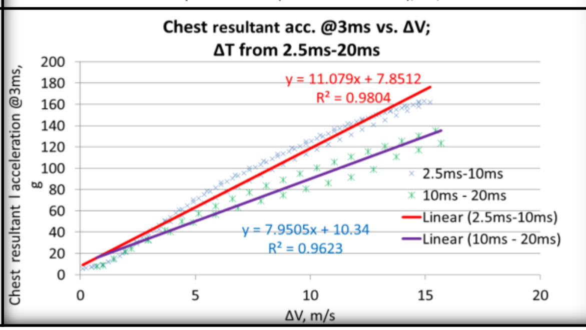


Seat w/ softer EA

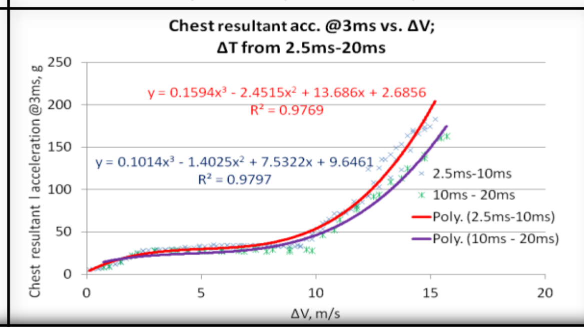


ΔV

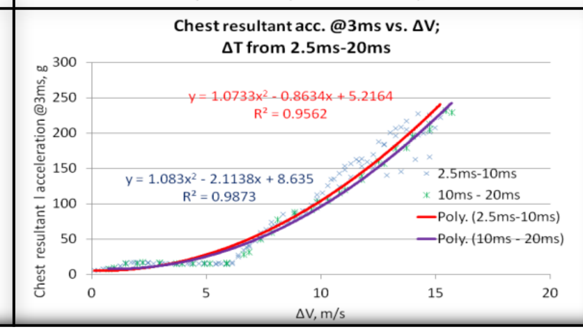
Rigid Seat



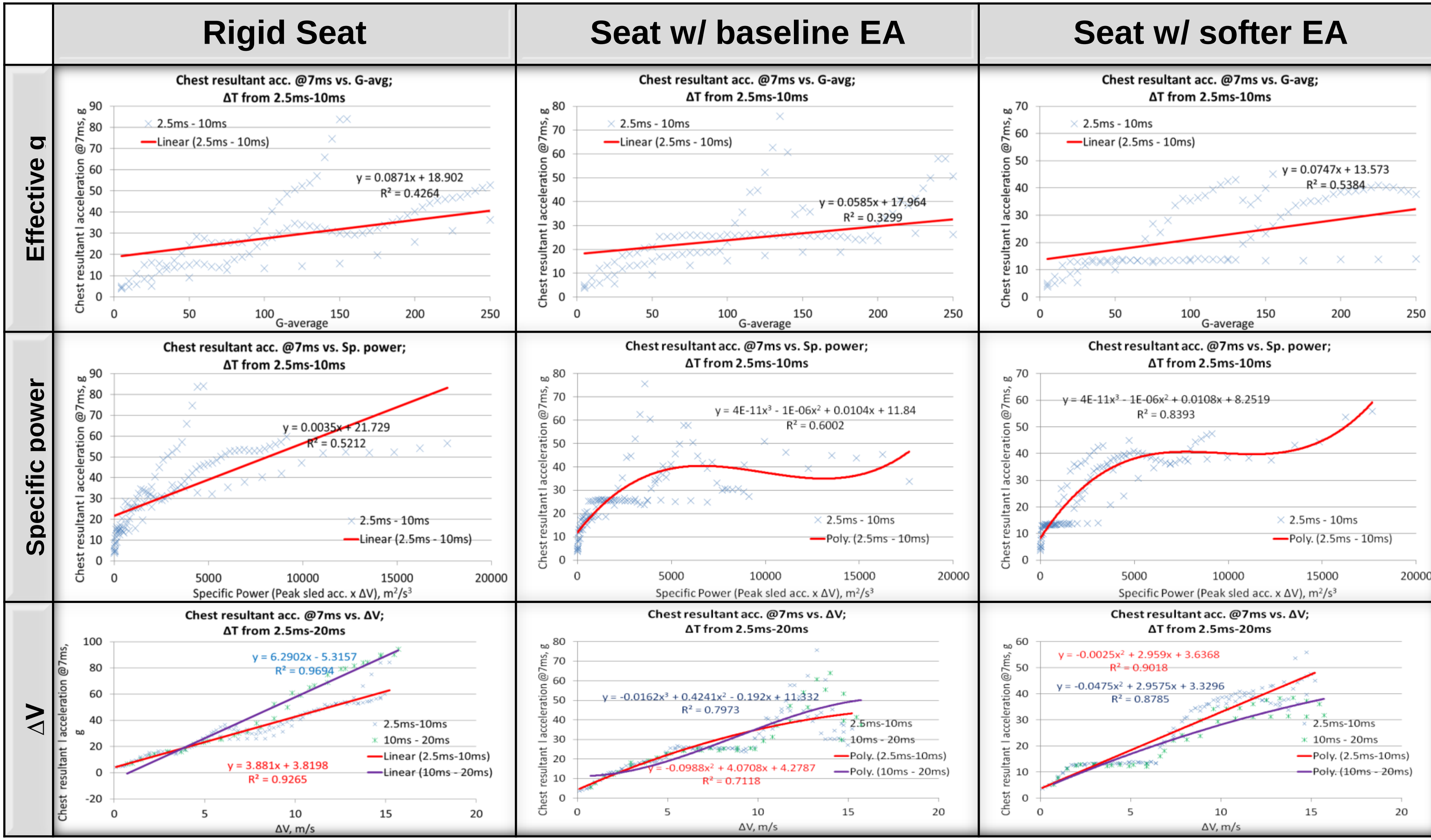
Seat w/ baseline EA



Seat w/ softer EA



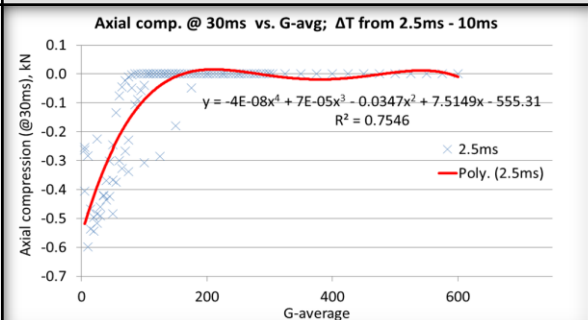
Chest resultant acc. (7ms-clip) Trend

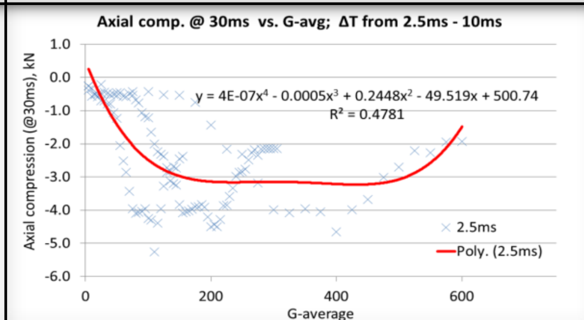


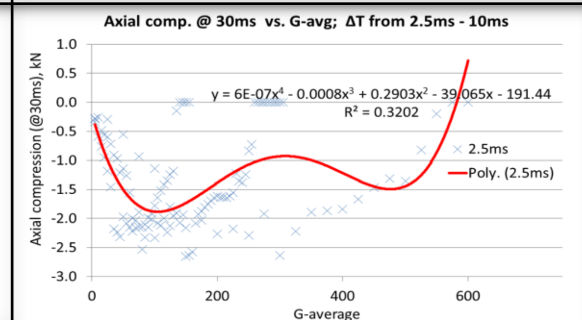
Lumbar comp. (30ms-clip) Trend

	Rigid Seat	Seat w/ baseline EA	Seat w/ softer EA

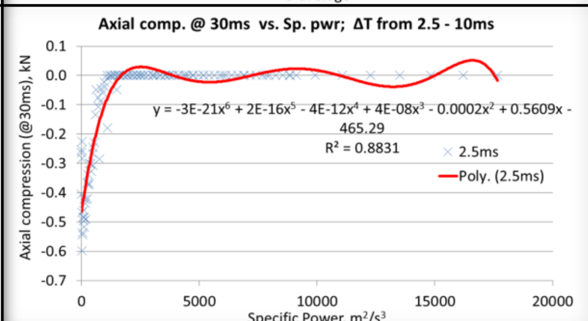
Effective g

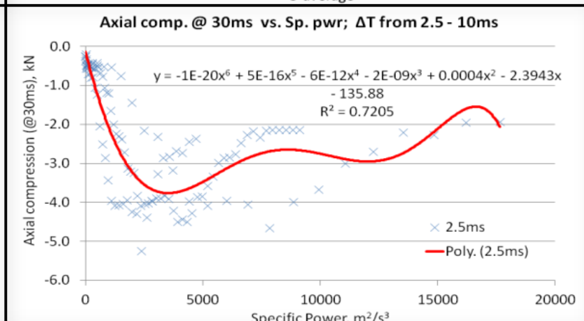


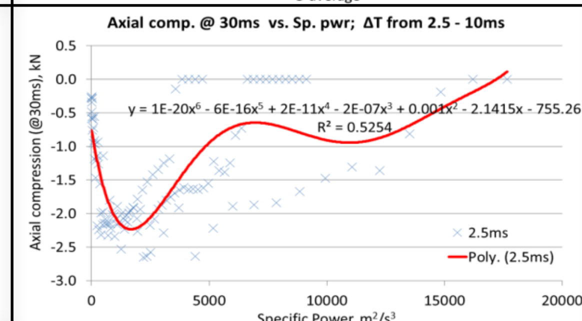




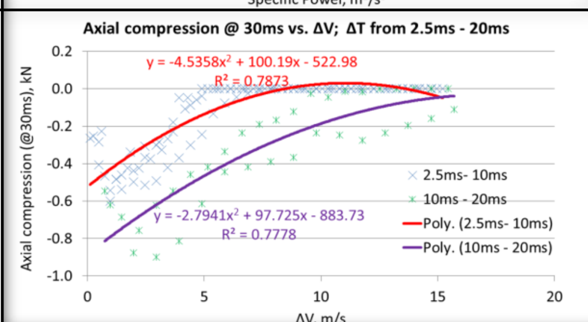
Specific power

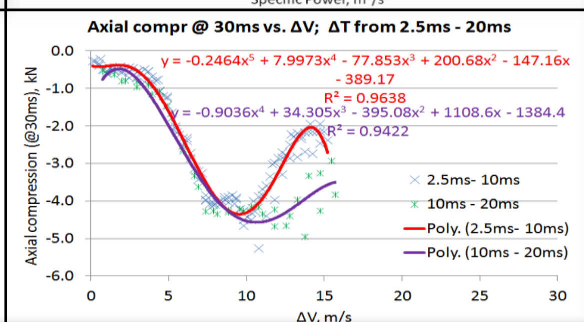


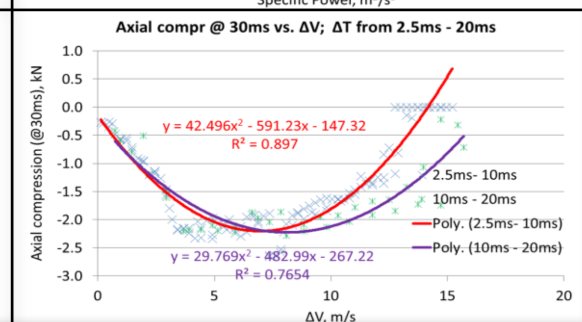




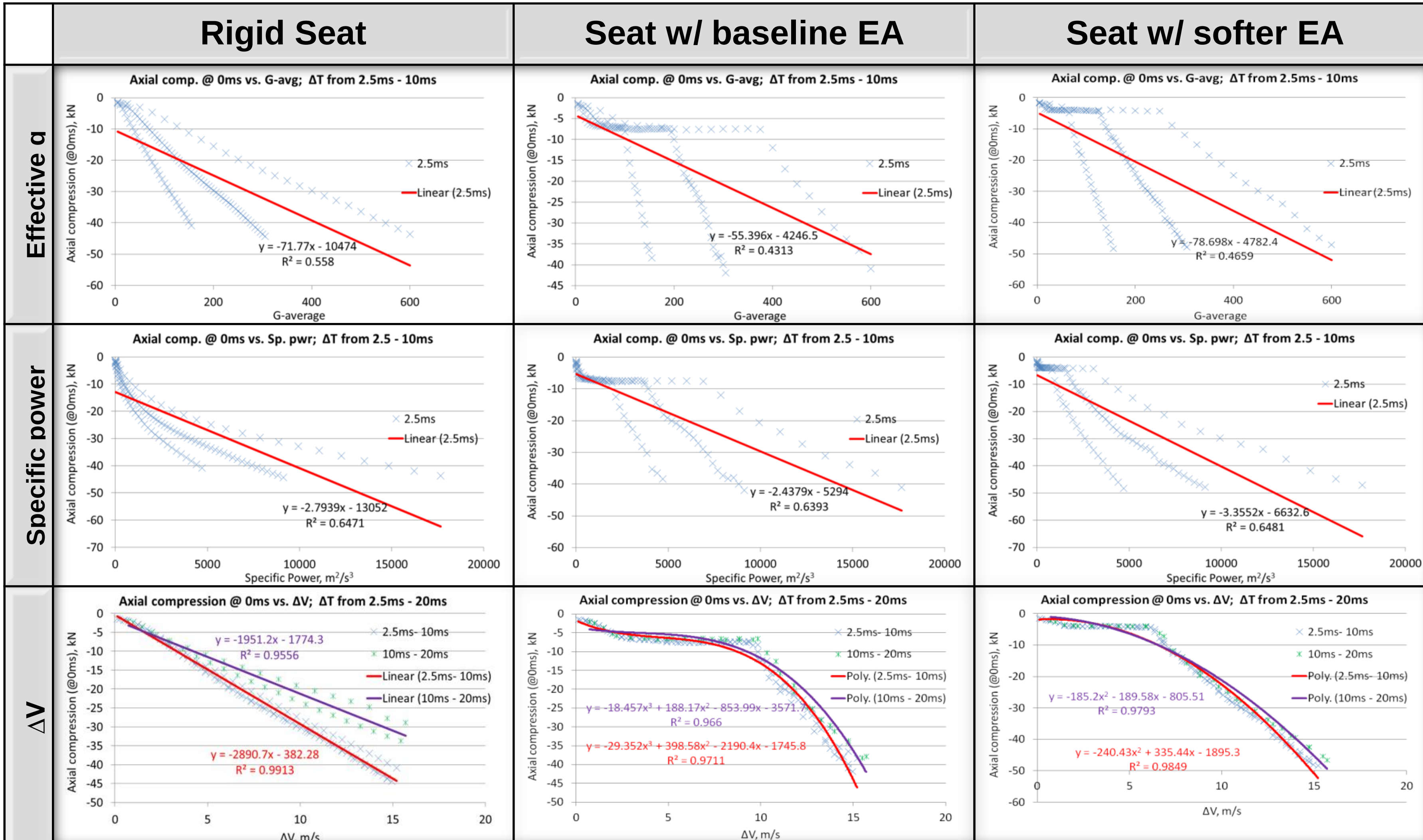
ΔV



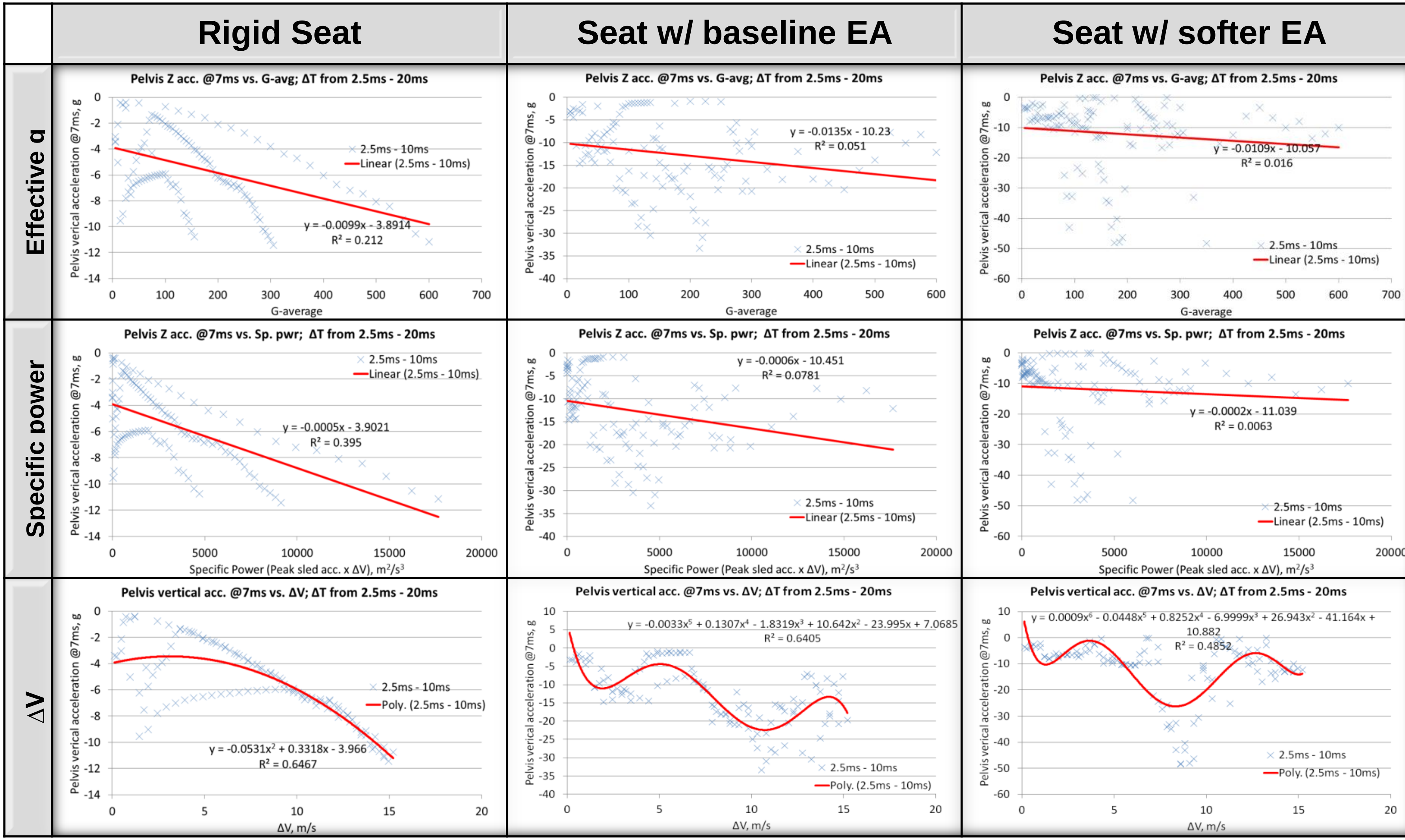




Lumbar compression (Peak) Trend



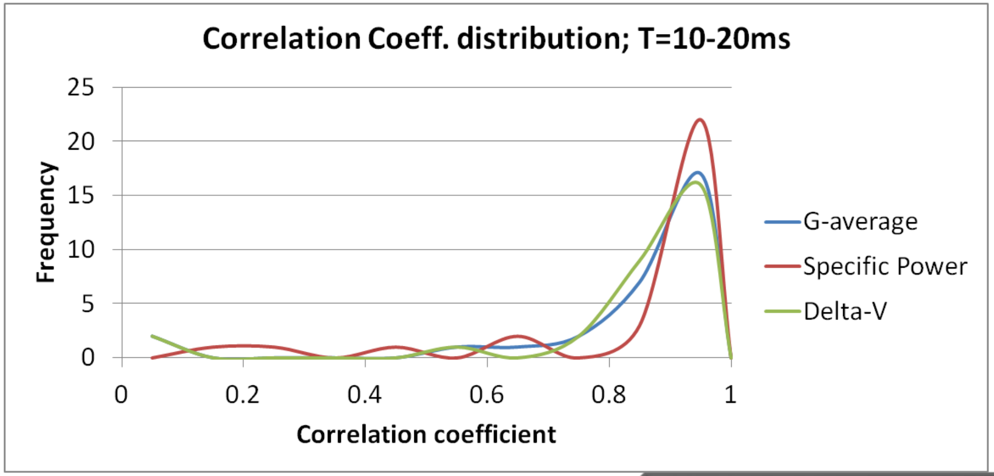
Pelvis vertical acc. (7ms-clip) Trend



Correlation coeff. (T = 10-20ms)

		Correlation Coefficients								
		T from 10-20ms								
		G-average			Specific power			ΔV		
		Rigid	EA1	EA2	Rigid	EA1	EA2	Rigid	EA1	EA2
1	HIC @15ms	0.94	0.73	0.86	0.99	0.85	0.95	0.95	0.75	0.90
2	Head resultant acceleration @2ms	0.98	0.83	0.92	0.98	0.92	0.96	0.99	0.85	0.96
3	Head resultant acclelaration @0ms	0.99	0.82	0.92	0.97	0.92	0.96	0.99	0.85	0.96
4	Neck injury criteria, N_{ij}	0.97	0.81	0.92	0.98	0.92	0.97	0.99	0.84	0.96
5	Chest resultant acceleration @3ms	0.99	0.84	0.92	0.94	0.93	0.98	0.98	0.87	0.96
6	Chest resultant acceleration @7ms	0.94	0.90	0.95	0.96	0.89	0.91	0.98	0.89	0.93
7	Lumbar spine compression @30ms	0.92	-0.77	0.09	0.84	-0.66	0.29	0.86	-0.82	0.04
8	Lumbar spine compression @0ms	-0.99	-0.84	-0.92	-0.96	-0.94	-0.97	-0.98	-0.88	-0.96
9	Pelvis vertical acceleration @7ms	-0.67	-0.55	-0.04	-0.62	-0.47	0.10	-0.76	-0.56	-0.06
10	DRI (Z)	0.96	0.95	0.94	0.96	0.97	0.97	1.00	0.98	0.98

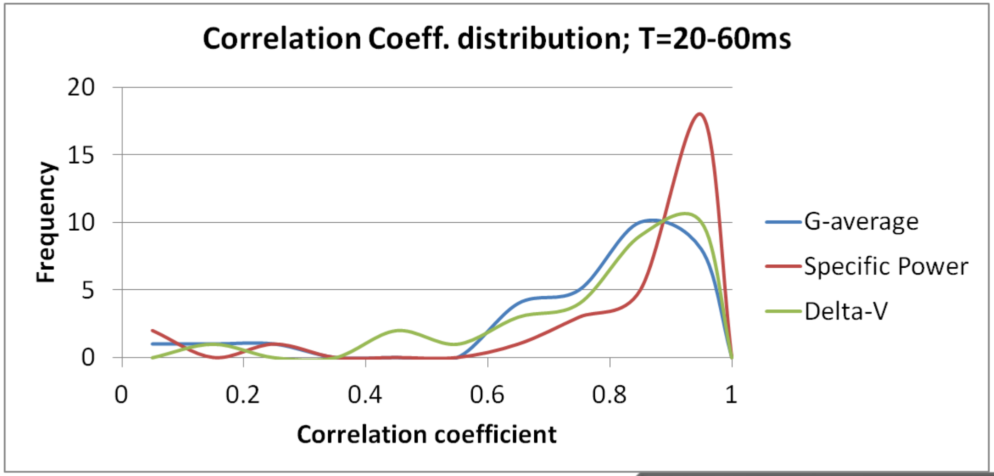
(pink)	0.5 < r < 0.75
(yellow)	0.75 < r < 0.9
(green)	r > 0.9



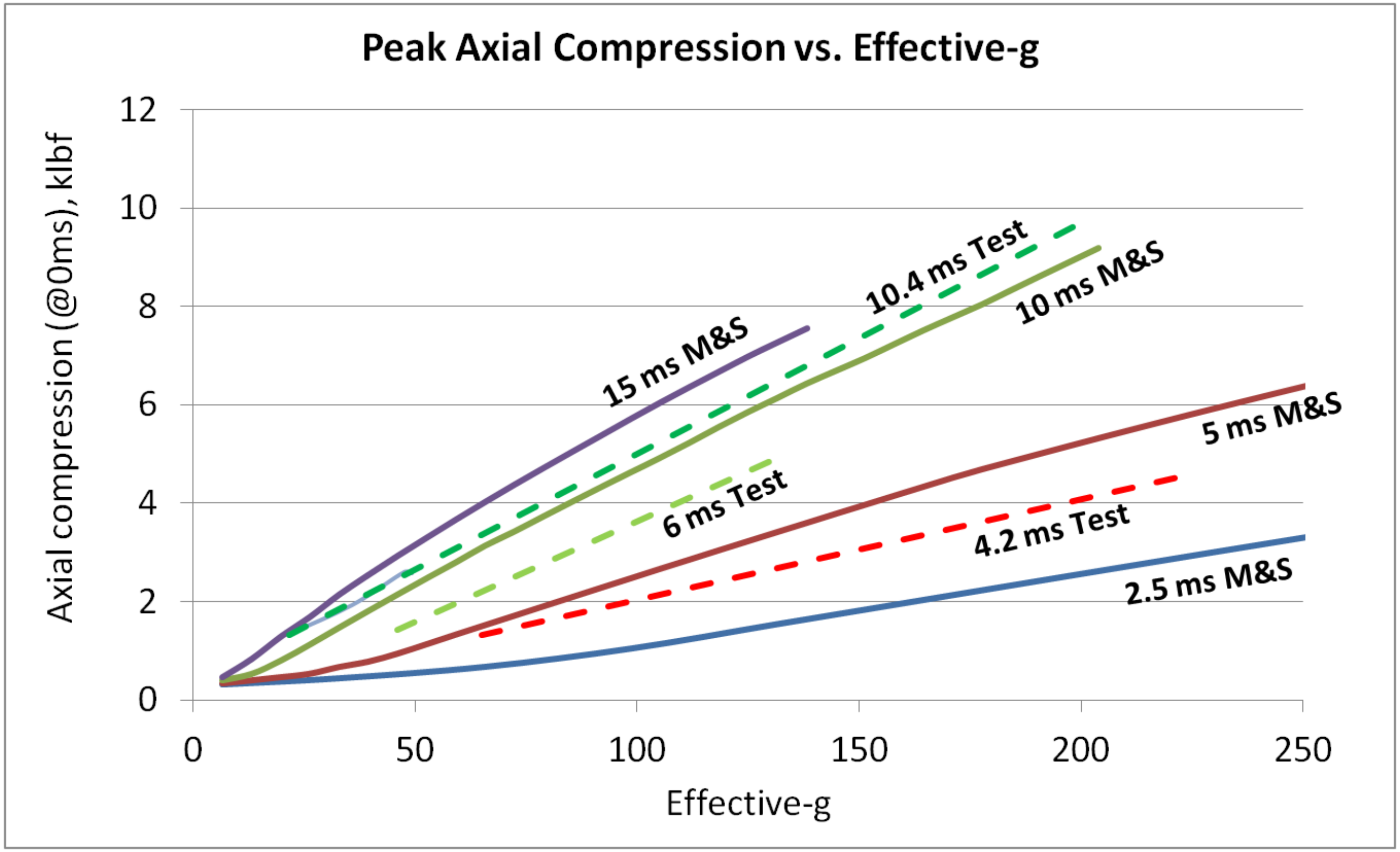
Correlation coeff. (T = 20-60ms)

		Correlation Coefficients T from 20-60ms								
		G-average			Specific power			ΔV		
		Rigid	EA1	EA2	Rigid	EA1	EA2	Rigid	EA1	EA2
1	HIC @15ms	0.96	0.69	0.82	0.98	0.77	0.93	0.77	0.53	0.82
2	Head resultant acceleration @2ms	0.98	0.79	0.88	0.98	0.88	0.96	0.86	0.68	0.92
3	Head resultant acclelaration @0ms	0.98	0.79	0.87	0.98	0.88	0.96	0.85	0.68	0.92
4	Neck injury criteria, N_{ij}	0.98	0.79	0.88	0.99	0.88	0.96	0.84	0.69	0.92
5	Chest resultant acceleration @3ms	0.97	0.80	0.86	0.98	0.90	0.95	0.88	0.74	0.92
6	Chest resultant acceleration @7ms	0.96	0.90	0.69	0.98	0.93	0.76	0.92	0.85	0.89
7	Lumbar spine compression @30ms	0.16	-0.69	-0.28	0.00	-0.67	-0.21	-0.41	-0.86	-0.40
8	Lumbar spine compression @0ms	-0.99	-0.79	-0.84	-0.96	-0.89	-0.93	-0.84	-0.74	-0.95
9	Pelvis vertical acceleration @7ms	-0.91	-0.69	-0.08	-0.94	-0.70	0.02	-0.94	-0.79	-0.15
10	DRI (Z)	0.89	0.90	0.86	0.93	0.95	0.94	0.99	0.95	0.96

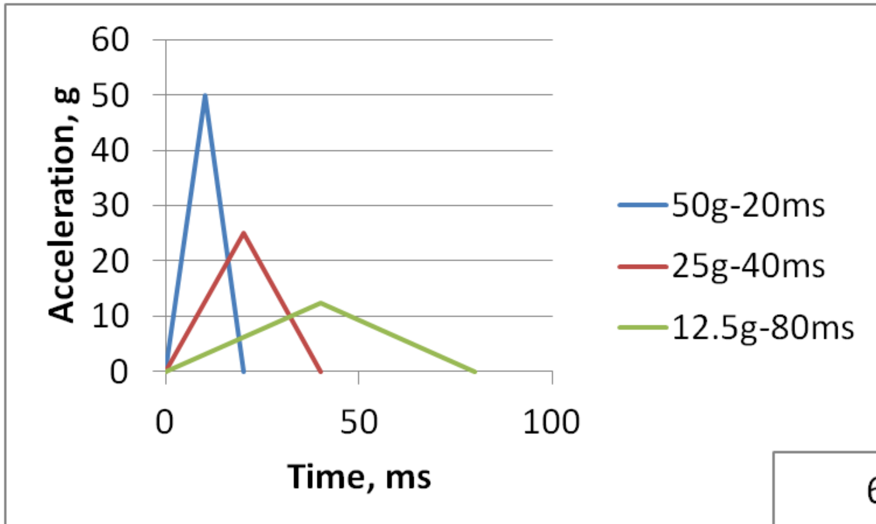
(pink)	0.5 < r < 0.75
(yellow)	0.75 < r < 0.9
(green)	r > 0.9



Lumbar compression vs. Effective-g

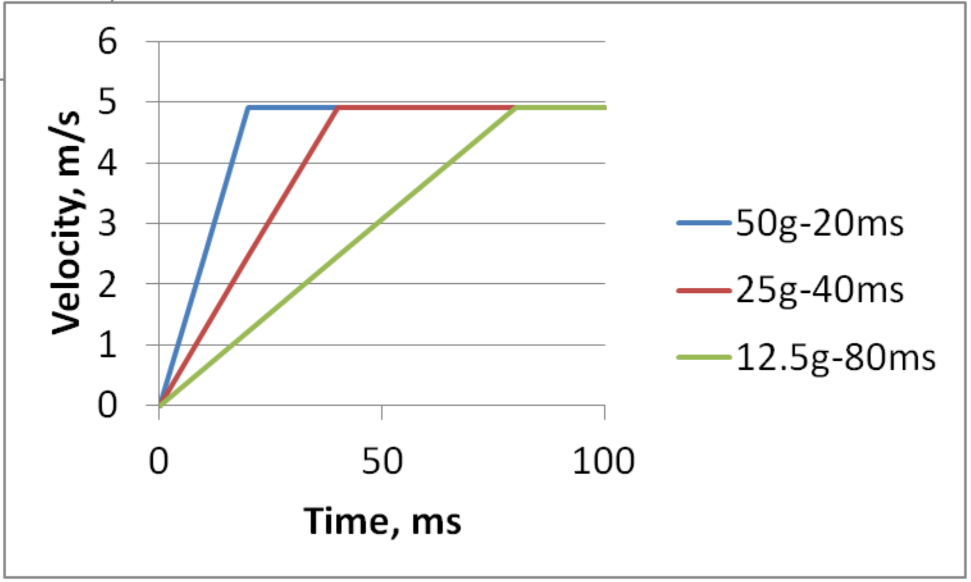


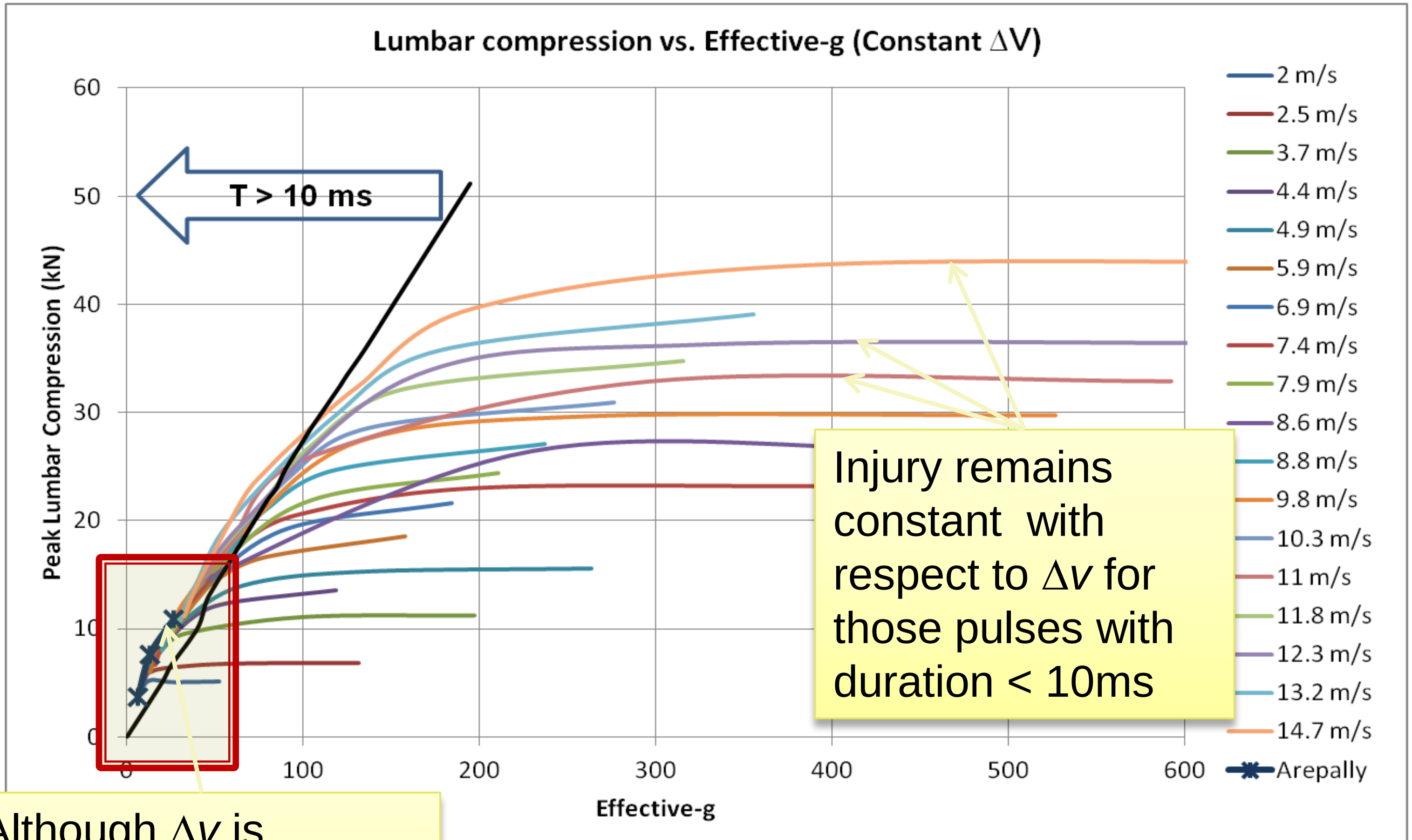
Lumbar compression from physical tests also do not show a good relationship with Effective-g. Dependence on *T* can be observed. Good correlation with M&S data can also be seen.



Three same three pulses with a constant Δ*v* of 4.9m/s and a duration of 20, 40 and 80ms taken from Ref 1 (Fig 14).

Effective-g for these pulses are 26.6, 13.3 and 6.65 g.

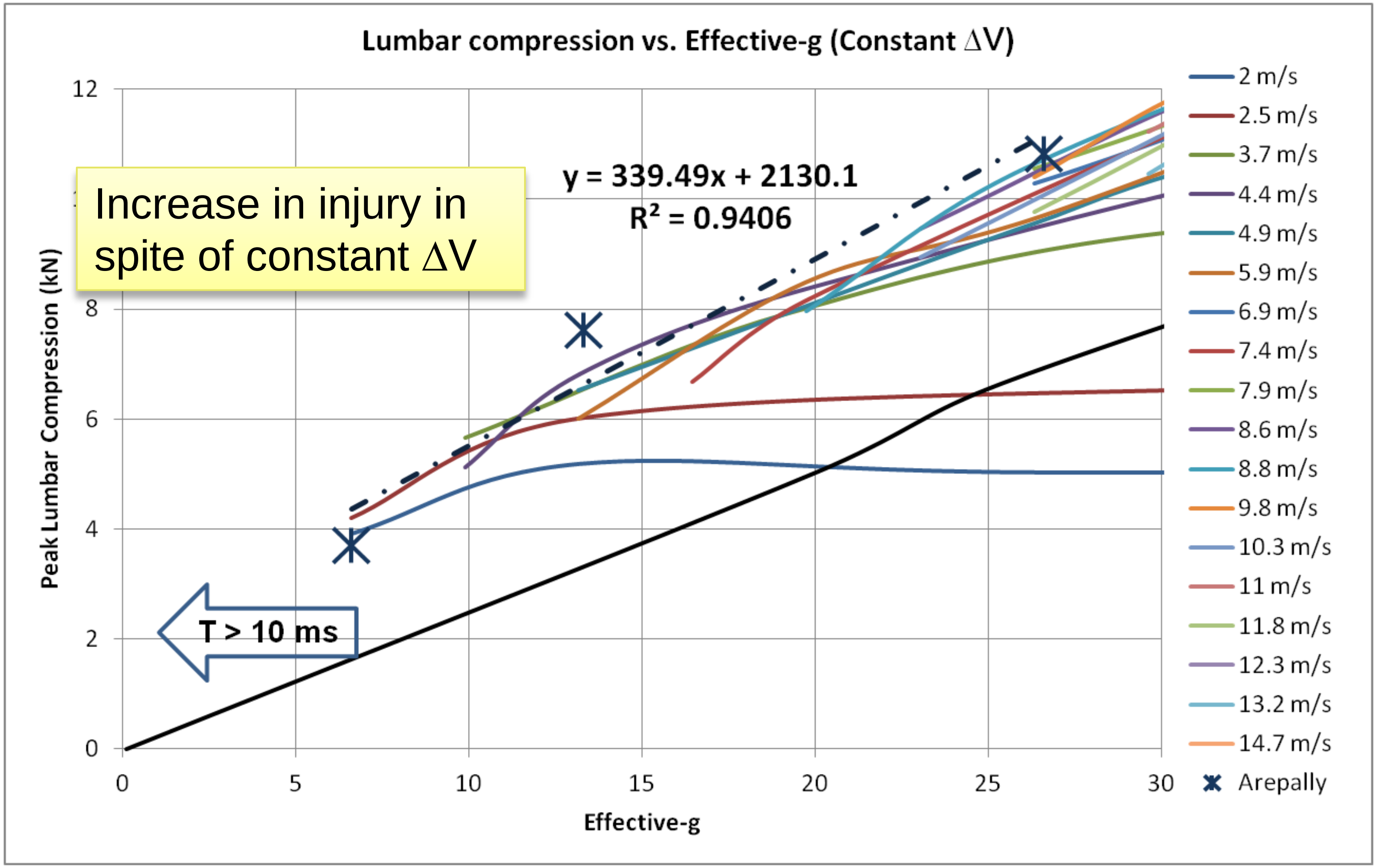




Injury remains constant with respect to Δ*v* for those pulses with duration < 10ms

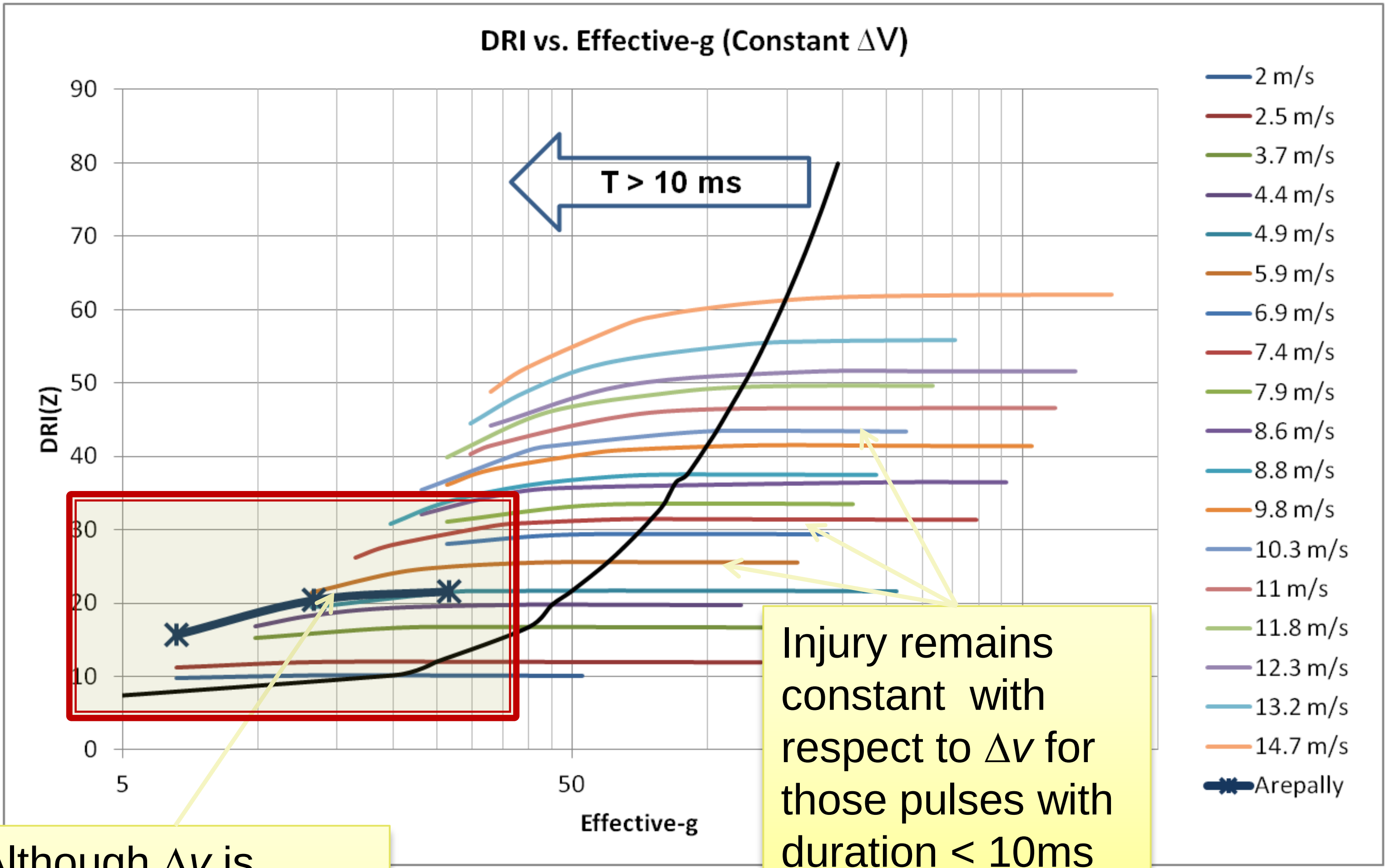
Although Δ*v* is constant, injury is increasing

Lumbar compression (Const Δv)



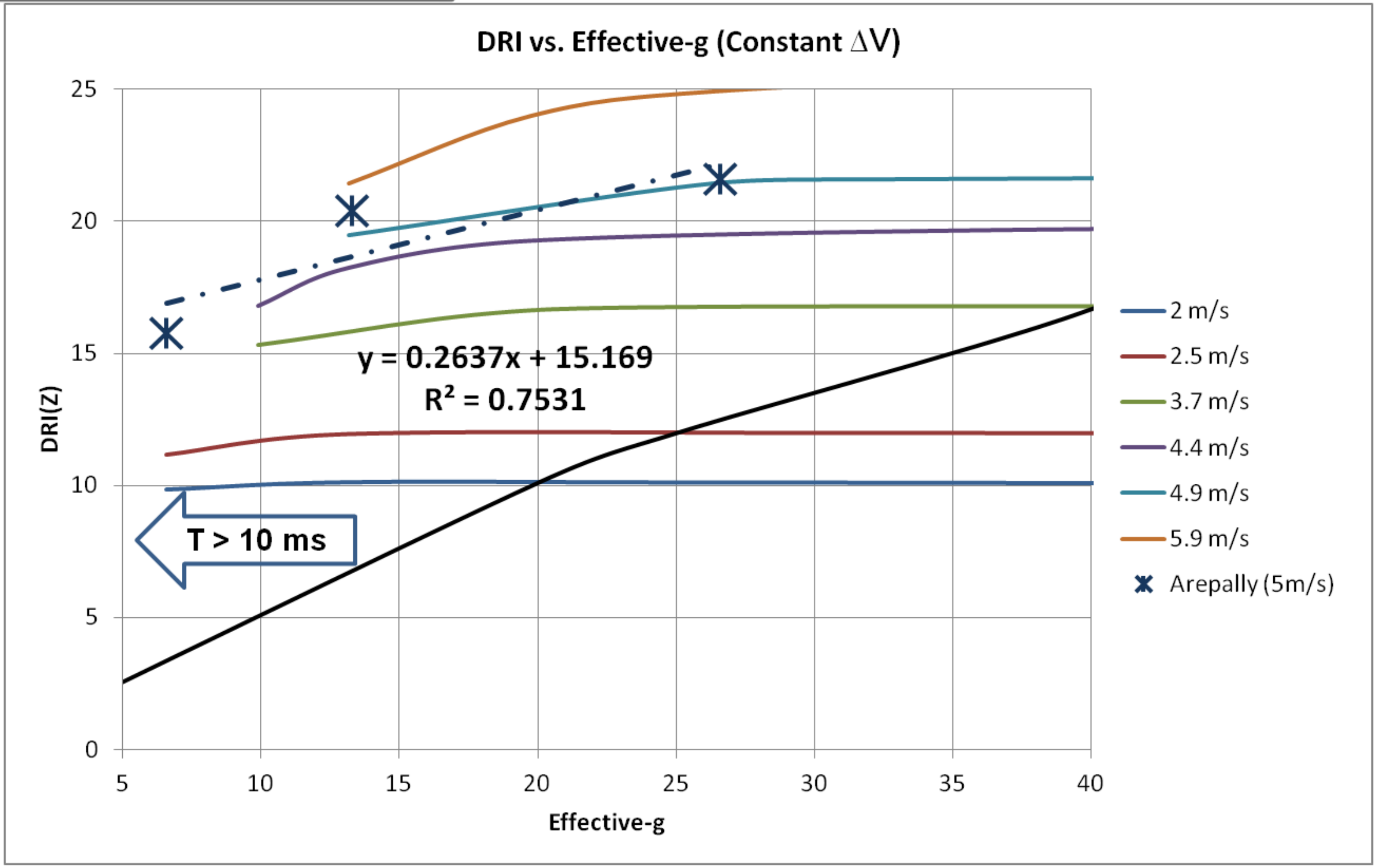
The three lumbar compression data points do show a good linear relationship with Effective-g (Ref . 1 Fig. 16).

DRI (Const Δv)



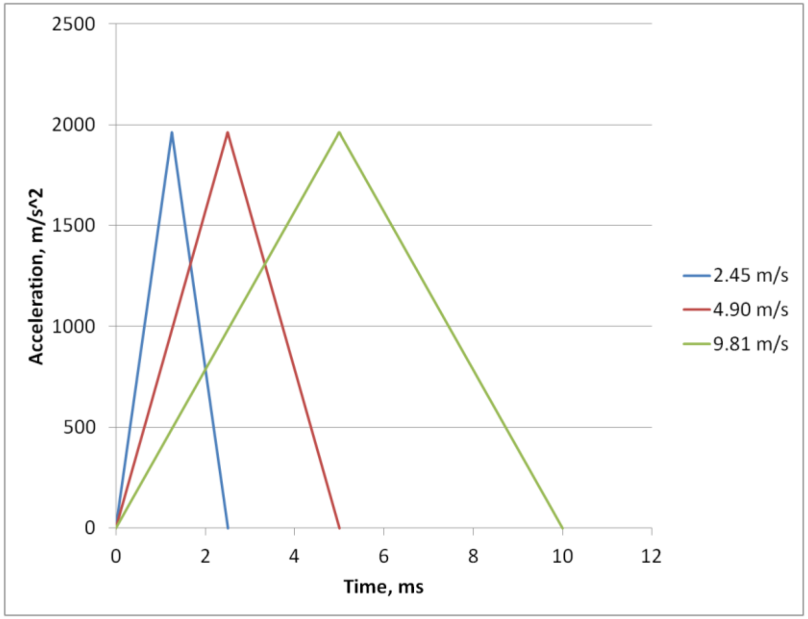
Injury remains constant with respect to Δv for those pulses with duration < 10ms

Although Δv is constant, injury is increasing



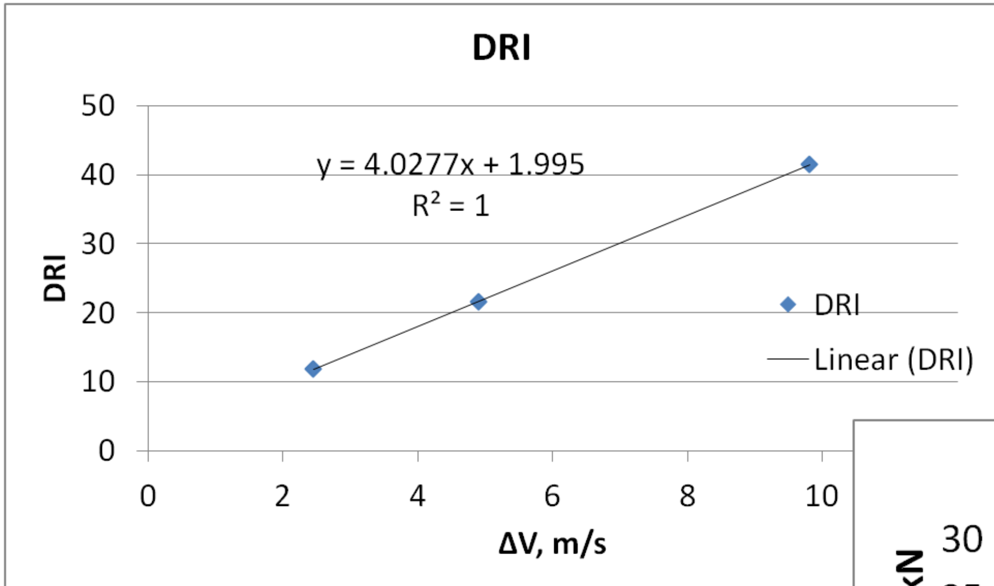
The three DRI data points do not show a good linear relationship with Effective-g (Ref . 1 Fig. 15).

Pulses with same Effective-g



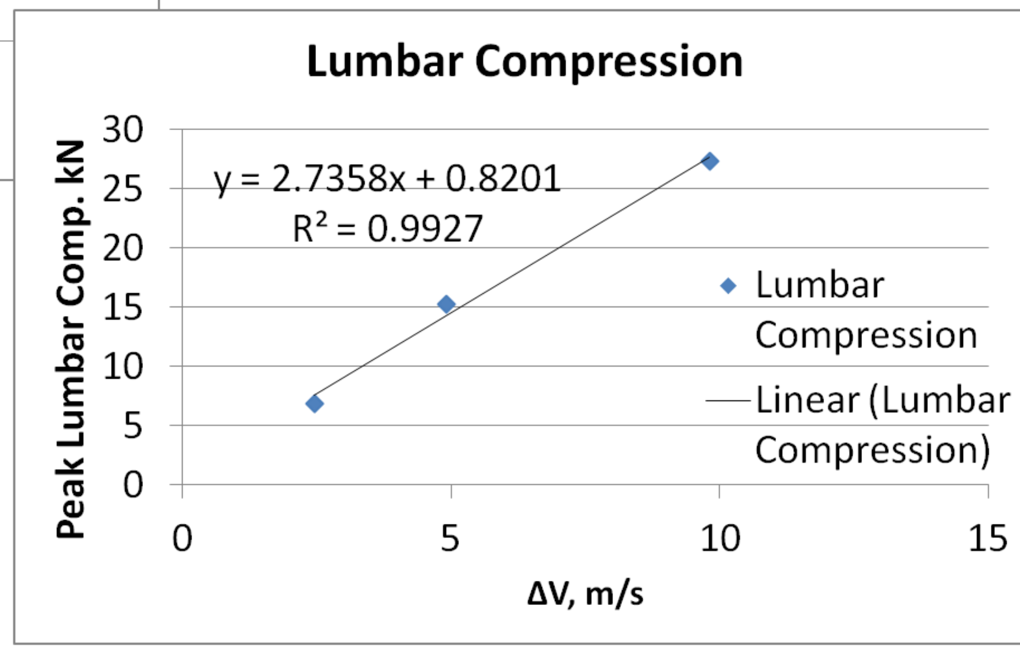
Three pulses are chosen such that peak acceleration for each is 200g and the duration of the pulses are 2.5, 5 and 10ms. Δv for these pulses are 2.45, 4.9 and 9.81 m/s. Effective-g for these pulses are all equal to 132 g.

Pulses with same Effective-g



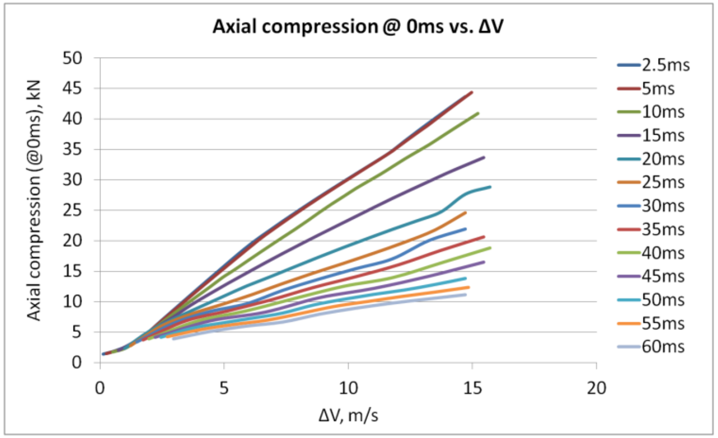
The three example pulses have the same effective-g of 132 but the injuries are not the same.

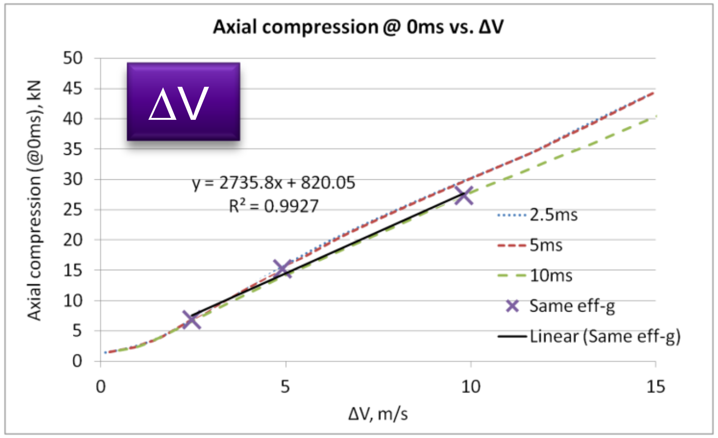
However, both these injuries demonstrate a linear relationship with Δv.



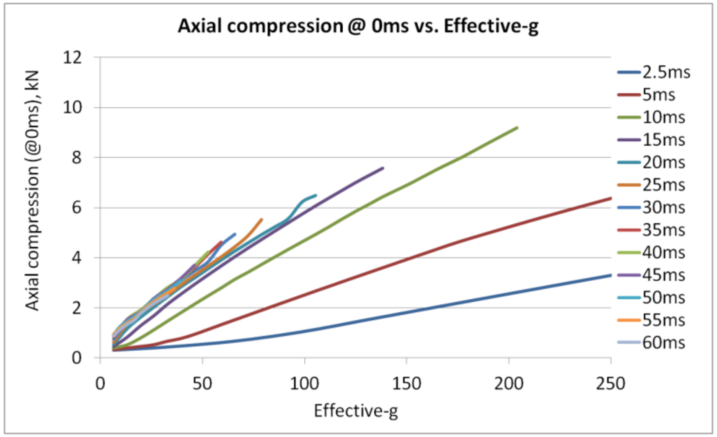
Pulses with same Effective-g

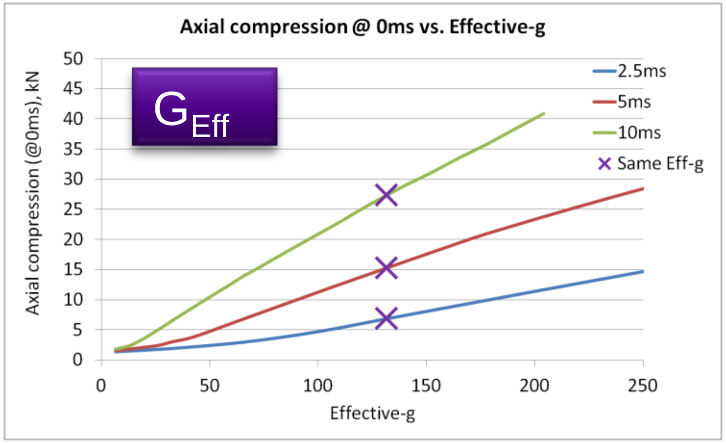
Injury results overlaid on the results from the parametric study





A linear relationship between injury and Δv





Occupant injury dependence on *T* is observed as reported in Ref #3.

Effect of loading paths (T = 10ms)

T = 10ms

Pulse iterations									HEAD			NECK	CHEST		PELVIS		LUMBAR SPINE	
									Resultant acceleration, g		HIC	N_{ij}	Resultant acceleration, g		Z-Acceleration, g	DRI (z), g	Axial compression, kN	
#	Pulse type	Peak, Dec., g	Duration, ms	Rate of onset, g/ms	ΔV, m/s	Sp. Pwr	Eff. G	G-avg	@ 2ms	@ 0ms	@ 15 ms	CFC 1000	@ 3ms	@ 7ms	@ 7ms		@30ms	@0ms
1	Triangular	175	10	35	8.6	1502	109	88	103.8	111.4	628	0.88	101.0	27.8	-5.9	36.4	0.0	-23.9
2	Haversine	175	10	35	8.6	1502	118	88	107.1	115.0	649	0.91	103.4	28.0	-5.5	36.4	0.0	-24.9
3	Sine	138	10	28	8.6	1180	105	88	101.7	109.1	621	0.86	99.3	29.9	-6.2	36.3	0.0	-24.1
4	Constant	91	10	NA	8.6	781	91	88	90.8	98.2	582	0.78	93.3	45.1	-20.0	36.4	0.0	-22.1
5	Triangular #2	175	10	35	8.6	1502	106	88	102.6	110.1	622	0.87	100.9	31.7	-4.8	36.4	0.0	-24.3
6	Triangular #3	175	10	35	8.6	1502	106	88	101.8	109.1	626	0.87	98.1	28.5	-8.5	36.5	0.0	-23.9
7	Triangular #4	175	10	35	8.6	1502	108	88	103.6	111.1	638	0.88	100.9	28.6	-6.0	36.7	0.0	-24.2
8	Triangular #5	175	10	35	8.6	1502	103	88	100.9	108.4	610	0.86	98.9	30.0	-6.0	36.2	0.0	-23.9

Including "Constant" type pulse

Mean, μ =	8.6	1372	105.6	87.5	101.5	109.1	621.9	0.9	99.5	31.2	-7.9	36.4	0.0	-23.9
Standard deviation, σ =	0.0	264	7.6	0.0	4.7	4.8	19.8	0.0	3.0	5.8	5.0	0.1	0.0	0.8
Coefficient of variation, C_v (%)	0%	19%	7%	0%	**5%**	**4%**	**3%**	**4%**	**3%**	**18%**	**64%**	**0%**	**0%**	**3%**

Excluding "Constant" type pulse

Mean, μ =	8.6	1456.0	107.7	87.5	103.1	110.6	627.6	0.9	100.4	29.2	-6.1	36.4	0.0	-24.2
Standard deviation, σ =	0.0	121.8	4.9	0.0	2.1	2.2	12.5	0.0	1.8	1.4	1.1	0.2	0.0	0.4
Coefficient of variation, C_v (%)	0%	8%	5%	0%	**2%**	**2%**	**2%**	**2%**	**2%**	**5%**	**19%**	**0%**	**0%**	**1%**

No path dependency of loading is observed on most of the injuries except pelvic clip values

Effect of loading paths (T = 40ms)

T = 40ms

#	Pulse type	Peak, Dec., g	Durat-ion, ms	Rate of onset, g/ms	ΔV, m/s	Sp. Pwr	Eff. G	G-avg	HEAD Resultant acceleration, g @ 2ms	HEAD Resultant acceleration, g @ 0ms	HEAD HIC @ 15 ms	NECK N_{ij} CFC 1000	CHEST Resultant acceleration, g @ 3ms	CHEST Resultant acceleration, g @ 7ms	PELVIS Z-Acceleration, g @ 7ms	PELVIS DRI (z), g	LUMBAR Axial compression, kN @30ms	LUMBAR Axial compression, kN @0ms
1	Triangular	44	40	2	8.6	376	27	22	54.6	55.4	223	0.46	47.4	42.0	-31.6	33.7	-1.3	-11.4
2	Haversine	44	40	2	8.6	375	29	22	62.2	63.7	274	0.53	50.0	49.2	-31.2	34.4	-1.0	-12.7
3	Sine	34	40	2	8.6	295	26	22	50.7	51.2	190	0.42	44.9	42.2	-28.0	33.3	-1.6	-10.7
4	Constant	23	40	NA	8.6	195	23	22	39.4	40.0	100	0.30	35.9	34.4	-25.0	31.4	-3.5	-8.5
5	Triangular #2	44	40	2	8.6	376	27	22	52.7	54.0	221	0.45	49.3	41.0	-24.7	33.3	-1.5	-11.5
6	Triangular #3	44	40	2	8.6	376	27	22	50.6	51.0	172	0.42	45.2	44.9	-30.9	33.3	-1.5	-10.1
7	Triangular #4	44	40	2	8.6	376	27	22	53.6	54.3	212	0.45	46.1	44.1	-31.3	33.8	-1.4	-11.2
8	Triangular #5	44	40	2	8.6	376	26	22	52.4	53.6	183	0.43	40.9	39.8	-30.8	33.1	-1.7	-10.8

Including "Constant" type pulse

	ΔV, m/s	Sp. Pwr	Eff. G	G-avg	Head @ 2ms	Head @ 0ms	HIC @ 15 ms	N_{ij}	Chest @ 3ms	Chest @ 7ms	Pelvis Z @ 7ms	DRI (z)	Lumbar @30ms	Lumbar @0ms
Mean, μ =	8.6	343	26.4	21.9	52.0	52.9	196.9	0.4	45.0	42.2	-29.2	33.3	-1.7	-10.9
Standard deviation, σ =	0.0	66	1.9	0.0	6.3	6.5	50.3	0.1	4.6	4.3	2.9	0.9	0.8	1.2
Coefficient of variation, C_v (%)	0%	19%	7%	0%	**12%**	**12%**	**26%**	**15%**	**10%**	**10%**	**10%**	**3%**	**45%**	**11%**

Excluding "Constant" type pulse

	ΔV, m/s	Sp. Pwr	Eff. G	G-avg	Head @ 2ms	Head @ 0ms	HIC @ 15 ms	N_{ij}	Chest @ 3ms	Chest @ 7ms	Pelvis Z @ 7ms	DRI (z)	Lumbar @30ms	Lumbar @0ms
Mean, μ =	8.6	364.0	26.9	21.9	53.8	54.7	210.7	0.5	46.3	43.3	-29.8	33.6	-1.4	-11.2
Standard deviation, σ =	0.0	30.5	1.2	0.0	4.0	4.3	34.1	0.0	3.1	3.1	2.5	0.4	0.2	0.8
Coefficient of variation, C_v (%)	0%	8%	5%	0%	**7%**	**8%**	**16%**	**8%**	**7%**	**7%**	**9%**	**1%**	**16%**	**7%**

No path dependency of loading is observed except lumbar clip values and HIC_{15}